THE DECENNIAL PUBLICATIONS OF THE UNIVERSITY OF CHICAGO

THE STUDY OF STELLAR EVOLUTION

HALE

THE DECENNIAL PUBLICATIONS OF
THE UNIVERSITY OF CHICAGO

THE DECENNIAL PUBLICATIONS

ISSUED IN COMMEMORATION OF THE COMPLETION OF THE FIRST TEN YEARS OF THE UNIVERSITY'S EXISTENCE

AUTHORIZED BY THE BOARD OF TRUSTEES ON THE RECOMMENDATION OF THE PRESIDENT AND SENATE

EDITED BY A COMMITTEE APPOINTED BY THE SENATE

THESE VOLUMES ARE DEDICATED

TO THE MEN AND WOMEN
OF OUR TIME AND COUNTRY WHO BY WISE AND GENEROUS GIVING
HAVE ENCOURAGED THE SEARCH AFTER TRUTH
IN ALL DEPARTMENTS OF KNOWLEDGE

THE STUDY OF STELLAR EVOLUTION

PLATE I

The Great Nebula in *Andromeda*

Photographed with the 24-inch reflecting telescope of the Yerkes Observatory (Ritchey)

THE STUDY OF STELLAR EVOLUTION

AN ACCOUNT OF SOME RECENT METHODS OF ASTROPHYSICAL RESEARCH

BY

GEORGE ELLERY HALE

FORMERLY OF THE DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS
NOW DIRECTOR OF THE MOUNT WILSON SOLAR OBSERVATORY

THE DECENNIAL PUBLICATIONS
SECOND SERIES VOLUME X

CHICAGO
THE UNIVERSITY OF CHICAGO PRESS
1908

A 224445

Entered at Stationers' Hall

Published May 1908

Composed and Printed By
The University of Chicago Press
Chicago, Illinois, U. S. A.

PREFACE

As first planned, this book was intended to serve as a handbook to the Yerkes Observatory. Many inquiries regarding the observatory's work, made by the numerous visitors received there annually, seemed to call for a printed explanation of the purposes in view and the observational methods employed. Removal to California and new duties connected with the organization of the Mount Wilson Solar Observatory caused a modification of the project. I finally adopted the plan of describing a connected series of investigations, laying special stress on the observational methods employed, in the hope of explaining clearly how the problem of stellar evolution is studied. The advantage of using concrete illustrations drawn, in large part, from personal experience, and the desire that the book should be of special service to visitors at the Yerkes and Mount Wilson Observatories, are sufficient reasons, I trust, for the otherwise undue proportion of space devoted to these institutions.

The omission of such important subjects as the theories of temporary and variable stars; Sir George Darwin's discussions of evolution as affected by tidal friction; Vogel's and Pickering's photometric and spectroscopic studies, and the researches of the latter on the distribution of stars of various types; Campbell's investigations of stellar spectra, and, to mention no other work, his development of the spectrographic method of determining radial velocities, sufficiently indicate that I have made no attempt to deal with the general problem of stellar evolution, or to offer anything approaching an adequate description of the observational methods of astrophysics. The various researches described are chosen rather arbitrarily, in some cases with more regard for my personal

acquaintance with the facts than because of their intrinsic importance. I trust, however, that although this method of treatment has necessarily resulted in a fragmentary exposition of the subject, the book will serve to show how the problem of stellar evolution is attacked along converging lines, leading from solar, stellar, and laboratory investigations.

I wish to express my thanks to Sir William Huggins; to Messrs. Adams, Ellerman, Olmsted, and Ritchey of the Mount Wilson Solar Observatory; to Professors Barnard, Burnham, and Frost of the Yerkes Observatory; to Professor Campbell of the Lick Observatory; to Professor Pickering of Harvard College Observatory; to Mr. Abbot of the Smithsonian Astrophysical Observatory; to Professor Lord of the Emerson McMillin Observatory; and to Professor Ames, Mr. Jewell of Johns Hopkins University, for photographs which appear in the plates. I am also indebted to the *Astrophysical Journal* and the *Publications of the Yerkes Observatory* for many cuts, and to Messrs. Ticknor & Co. for permission to reproduce Langley's drawing of a typical sun-spot. I am under special obligations to my colleague. Mr. Ellerman, to whom are due most of the photographs of instruments, buildings, and landscapes which appear in the plates, besides many of the solar and stellar photographs taken from our joint papers in the *Astrophysical Journal* and elsewhere.

G. E. H.

PASADENA, CALIFORNIA
November, 1907

CONTENTS

CHAPTER		PAGE
I.	The Problem of Stellar Evolution	1
II.	The Student of the New Astronomy	9
III.	The Sun as a Typical Star	15
IV.	Large and Small Telescopes	20
V.	Astronomical Photography with Camera Lenses	27
VI.	Development of the Reflecting Telescope	38
VII.	Elementary Principles of Spectrum Analysis	46
VIII.	Grating Spectroscopes and the Chemical Composition of the Sun	56
IX.	Phenomena of the Sun's Surface	67
X.	The Sun's Surroundings	73
XI.	The Spectroheliograph	82
XII.	The Yerkes Observatory	97
XIII.	Astronomical Advantages of High Altitudes	111
XIV.	The Mount Wilson Solar Observatory	121
XV.	The Snow Telescope	131
XVI.	Some Uses of Spectroheliograph Plates	139
XVII.	A Study of Sun-Spots	151
XVIII.	Stellar Temperatures	165
XIX.	The Nebular Hypothesis	175
XX.	Stellar Development	187
XXI.	The Meteoritic and Planetesimal Hypotheses	204
XXII.	Does the Solar Heat Vary?	212
XXIII.	The Construction of a Large Reflecting Telescope	219
XXIV.	Some Possibilities of New Instruments	230
XXV.	Opportunities for Amateur Observers	243
Index		251

CHAPTER I

THE PROBLEM OF STELLAR EVOLUTION

It is not too much to say that the attitude of scientific investigators toward research has undergone a radical change since the publication of the *Origin of Species*. This is true not only of biological research, but to some degree in the domain of the physical sciences. Investigators who were formerly content to study isolated phenomena, with little regard to their larger relationships, have been led to take a wider view. As a consequence, the attractive qualities of scientific research have been greatly multiplied. Many a student, who could see in a museum only a wilderness of dry bones, now finds each fragment of profound interest if the part it plays in a general scheme of evolution can be made clear. The color and structure of any animal or plant, the minute modifications which distinguish one variety from another, take on new significance when considered as evidences of development. Their appeal to the microscopist, or to anyone who finds delight in intricacy of structure or beauty of form, is quite as great as before. But to the student whose interest is not aroused by such details, perhaps from lack of technical knowledge, or from the feeling that these matters are trivial as compared with the larger problems of science. such minor peculiarities must appear in a new light. Their true significance becomes apparent, and the importance of studying them, once perhaps underestimated, now requires no demonstration.

In astronomy the idea of evolution goes back to a very early period. In a crude and grotesque form the traditions of the earliest peoples invariably struggle to account for the

origin of the Earth and its inhabitants. On a much higher plane stand the speculations of the Greek philosophers and of those who have followed them in the centuries preceding our own time. All schools of astronomers, dealing in some instances with purely philosophical and theoretical considerations, and in others basing their conclusions upon known facts of observation, have sought in their turn to explain the origin of the solar system and the larger relationships that obtain in the universe as a whole. In the eighteenth century these speculations reached their climax in the nebular hypothesis of Laplace, which still remains as the most serious attempt to exhibit the development of the solar system. Attacked on many grounds, and showing signs of weakness that seem to demand radical modification of Laplace's original ideas, it nevertheless presents a picture of the solar system which has served to connect in a general way a mass of individual phenomena, and to give significance to apparently isolated facts that offer little of interest without the illumination of this governing principle.

It will be seen, therefore, that the idea of evolution and development is by no means new to the astronomer. But it may nevertheless be maintained that it has occupied a more important position since Darwin published his great work. In 1859, the very year of the publication of the *Origin of Species*, Kirchhoff first succeeded in determining the chemical composition of the Sun by the aid of the spectroscope. His fundamental discovery marked the entrance of this instrument into the field of astronomical research and established on a firm basis the new science of astrophysics. The importance of spectroscopic investigations in their relationship to evolution was soon made clear. Within a single decade the study of stellar spectra by Huggins, Rutherfurd, and Secchi had shown that the stars may be divided into several classes, characterized by distinctive peculiarities in their luminous

emission and marking definite stages in an orderly process of development. Following close upon this pioneer work came the capital discovery by Huggins of the gaseous nature of the nebulae, and the relationship of these celestial clouds to the stars which they enshroud. In these filmy masses of luminous gas it appeared probable that the stars had their origin, taking form after long ages of condensation, through processes regarding which our ideas are still vague and ill defined. Belief in such a mode of development has been greatly strengthened through the results of recent investigations, and especially through the discovery by Keeler that of 120,000 nebulae strewn over the heavens fully one-half are distinctly spiral in form. This far-reaching conclusion, coming at the end of the nineteenth century, is furnishing materials for those who seek, through modification of the nebular hypothesis, to provide a sound and sufficient explanation of the development of suns like our own.

We are now in a position to regard the study of evolution as that of a single great problem, beginning with the origin of the stars in the nebulae and culminating in those difficult and complex sciences that endeavor to account, not merely for the phenomena of life, but for the laws which control a society composed of human beings. Any such consideration of all natural phenomena as elements in a single problem must begin with a study of the Sun, the only star lying near enough the Earth to permit of detailed investigation. The knowledge thus derived may then be applied in researches on the nebulae, and in the elucidation of spectroscopic observations of those stars which represent the early period of stellar existence. According to present views, the state of development attained by the Sun is that of maturity, if not of decline. After it come the red stars, which represent the last stages of luminous stellar life. Even the extinction of light due to continued cooling is not sufficient to exclude

altogether from the astrophysicist's study those dying stars which represent a condition lying between that of a glowing sun and a dead planet like the Earth or the Moon. Through one of its many remarkable properties, the spectroscope enables us to detect the presence, and sometimes to determine the dimensions, of vast bodies which have resulted from the cooling of former suns. It will be the object of this book to show how the student of astrophysics attacks this problem of stellar evolution, through the development of special instruments and methods of research, and the accumulation and discussion of observations.

It must not be forgotten that such a study comprises only the earliest and simplest elements in the general problem of evolution. The province of the student of astrophysics may be said to end with an understanding of the production of a planet like the Earth. It remains for the geologist to explain the changes which the surface of the Earth has undergone since the constructive process left it a rocky crust. The conditions which brought about the formation of the oceans, the effects of the long-continued action of winds and waves, and the vast changes in surface structure that have resulted from internal disturbances and the operation of volcanic phenomena, afford limitless opportunity to the student of evolution in this other aspect. Closely related to these changes, and presenting difficulties far greater than those experienced by the astrophysicist, comes the problem of accounting for the origin and development of plant and animal life. The preservation of the earlier forms of life, principally through the agency of sedimentary deposits, affords the paleontologist the means of connecting the links in the evolutionary chain. Thus we are brought to our own era, where countless living objects continue to supply material for new inquiries. Both in the examination of existing species and their relationships, and in those experimental researches on variation which offer

such promising opportunities to the investigator, the evolutionist may secure data for further advances. Outside the immediate domain of the natural sciences, in regions of activity where still greater complexity prevails, the student may seek to trace out evidences of unity and development in the mental and moral relationships of the peoples of many countries and of many generations.

It is a noteworthy fact, of prime significance to all investigators who find special interest in attempting to enter new and unoccupied fields, that some of the most important developments of recent years have taken place in those regions which lie between the boundaries of the old established sciences. Thus the union of physics and chemistry has opened up the extensive field of physical chemistry, where advances of the greatest value are being made. In the same way the application of physical methods and the principles of physical chemistry to the experimental study of physiology has resulted so successfully as to give hope for even more remarkable developments in the near future. In astronomy, the introduction of physical methods has revolutionized the observatory, transforming it from a simple observing station into a laboratory, where the most diverse means are employed in the solution of cosmical problems. The fact that physics is common to these and other intermediate branches of science affords striking proof of its fundamental importance. An investigator who has been confined to the traditional methods of a department of science where physics has as yet played little part, may therefore find in physical methods a powerful means of advancing his subject.

The suggestive value, to investigators in other departments, of any species of scientific research which involves new methods and principles is perhaps greater at the present time than ever before. Even those methods of research which can find no direct application in other subjects are

frequently capable of suggesting modifications or adaptations involving related principles. The development and use of new methods is quite as likely to advance a subject as the prosecution of extensive investigations by existing means. For this reason the investigator is ever on the alert to seize and utilize suggestions derived from any source.

The interest of the student of astrophysics is no longer confined simply to celestial phenomena. For astrophysics has become, in its most modern aspect, almost an experimental science, in which some of the fundamental problems of physics and chemistry may find their solution. The stars may be regarded as enormous crucibles, in some of which terrestrial elements are subjected to temperatures and pressures far transcending those obtainable by artificial means. In the Sun, which appears to us not merely as a point of light like the stars, but as a vast globe whose every detail can be studied in its relationship to the general problem of the solar constitution, the immense scale of the phenomena always open to observation, the rapidity of the changes, and the enormous masses of material involved, provide the means for researches which could never be undertaken in terrestrial laboratories. Hence it is that astrophysics may equally well be regarded as a branch of physics or as a branch of astronomy. A telescope may be defined as an instrument for revealing celestial phenomena, or it may be likened to the lens which the physicist uses in his laboratory to concentrate the light of an electric spark on the slit of his spectroscope. To the student of astrophysics whose interests are not confined to a single branch of science, the subject is likely to make a double appeal, no less strong on the physical and chemical than on the astronomical side.

In entering upon our consideration of the study of stellar development, we may think of the subject in either one of two ways. Some will prefer to regard it as the general prob-

lem of stellar evolution, in its broad application to the universe at large. But others will find it easier to conceive of the question as an investigation of the Sun, tracing it, through analogies afforded by stars in earlier stages of growth, from its origin in a nebula to those final chapters which, though not yet written for the Sun itself, may be read in the life-histories of the red stars. Viewed from whichever standpoint, the task of the investigator remains the same, since in either case it is concerned with stellar origin, development, and decay.

It must, of course, be remembered that the processes of stellar development ordinarily advance so slowly that a lifetime would be far too short to permit any permanent change to be observed in a star. Temporary stars flash into view and fade rapidly away; but these represent an abnormal condition, typical of some catastrophe rather than of a natural course of change. The spiral nebulae, though their appearance leaves little doubt of extremely rapid motion and constant change of form, are so far removed, and constructed on so vast a scale, that no actual differences in structure have been detected in photographs of the same object, taken at intervals of many years. In the processes of creation a thousand years is but a day, and we must be content to base our stellar histories upon analogy.

Fortunately, the data needed for the construction of these histories are easily found. Our problem is like that of one who enters a forest of oaks, and desires to learn through what stages the trees have passed in reaching their present condition. He cannot wait long enough to see any single tree go through its long cycle of change. But on the ground he may find acorns, some unbroken and some sprouting. Others have given rise to rapidly growing shoots, and saplings are at hand to show the next stage of growth. From saplings to trees is an easy step. Then may be found, in the

form of dead limbs and branches, the first evidences of decay, reaching its full in fallen trunks, where the hard wood is wasting to powder.

Scattered over the heavens are millions of stars, each representing a certain degree of development. The cloud forms of the nebulae tell us of stellar origins; the white, yellow, and red stars illustrate the rise and decline of stellar life; and the Earth itself affords a picture of what may remain after light and heat have been extinguished.

CHAPTER II

THE STUDENT OF THE NEW ASTRONOMY

THE traditional conception of the astronomer, while still applicable (with sundry limitations) in certain modern instances, does not accurately apply to the student of stellar evolution. According to the old view, the astronomer, soon after the setting of the Sun, retires to a lofty tower, from whose summit he gazes at the heavens throughout the long watches of the night. His eye, fixed to the end of a telescope tube, perceives wonders untold, while his mind sweeps with his vision through the very confines of the universe. The lineal descendant of the seers and soothsayers of the Chaldeans, he dwells apart, finding little of interest in the ordinary concerns of the world, so occupied are his thoughts with celestial mysteries.

Now there can be no doubt that the study of stellar evolution brings a degree of pleasure and enthusiasm which it would be difficult to surpass. The joys of the pioneer, the excitement that comes to him who looks for the first time upon an unknown land, the intense satisfaction of discovery, all belong to the successful investigator. Moreover, mere gazing through a telescope, as distinguished from the painstaking work of modern astronomers with micrometer or photographic plate, is still competent to reveal new or changing phenomena, and important discoveries are yet to come to the alert and careful observer. It is pleasant to picture the surprise and delight of Galileo when he first perceived spots on the supposedly immaculate surface of the Sun. His little instrument, much less perfect than a modern spy-glass, could reveal none of that intricate structure and exquisite

detail that are at once the joy and the despair of present-day sun-spot observers. But he had discovered a new and important fact, the basic principle of the science of astrophysics: he had shown that with suitable optical aid the *physical structure* of the heavenly bodies might be investigated. Prior to this time astronomy had concerned itself only with the positions and motions of the stars; now it became evident that each of these luminaries might present peculiar and distinguishing phenomena worthy of the most searching investigation. Discovery followed discovery in rapid sequence. The mottled face of the Moon, formerly without meaning, was suddenly revealed in unsuspected landscapes of valley, plain, and mountain, resembling, in curious degree, the variegated surface of the Earth. *Jupiter*, who had seemed to travel alone through the heavens, was found to possess four companions, whose revolutions about him forcibly suggested the revolutions of the planets about the Sun. The mysterious *ansae*, inclosing between them the globe of *Saturn*, were soon made out to be the more conspicuous elements of a vast incircling ring, unlike anything of earlier experience. With the growth of the telescope more marvels were brought to light, until it seemed, in sound reason, as though the universe would never cease to yield new knowledge to the explorer of its boundless wastes.

Thus was established that conception of the astronomer that still persists, long after a new astronomy has come into being. Gazing through a telescope, as has been said, is still competent to bring discoveries; for change is the very essence of celestial phenomena, and persistent watching must detect important facts, on which broad generalizations may be founded. But the eye and the telescope have been supplemented by various instrumental aids which, in their multiplication, have transformed the occupations of the astronomer. The micrometer, in its application to the accurate measure-

ment of place and form, permits changes to be detected which are beyond the perception of the eye. The photometer, in its precise determinations of brightness, has shown that stars whose light never varies are rather the exception than the rule. The photographic plate, used in conjunction with the telescope, has proved itself to be more sensitive than the human retina, in that it is capable of adding up into a visible record the invisible radiations received during an exposure of many hours. Finally, to mention but one more of the telescope's new adjuncts, the spectroscope has introduced a new and revolutionary principle into astronomy, permitting the chemical and physical analysis of the most distant stars.

Hence it is that the present-day student of astrophysics does not correspond to the traditional idea of the astronomer. His work at the telescope is largely confined to such tasks as keeping a star at the precise intersection of two cross-hairs, or on the narrow slit of a spectrograph, in order that stars and nebulae, or their spectra, may be sharply recorded upon the photographic plate. His most interesting work is done, and most of his discoveries are made, when the plates have been developed, and are subjected to long study and measurement under the microscope. His problems of devising new methods of calculation or reduction are as fascinating as the invention of new instruments of observation. Much of his time may be spent in the laboratory, imitating, with the means placed at his disposal by the physicist and chemist, the various conditions of temperature and pressure encountered in the stars, and watching the behavior of metals and gases in these uncommon environments. If, in the conviction that new and promising means of research are always awaiting application, he would advance into still unoccupied fields, he must devote himself to the design and construction of new instruments, to supplement the old. Kept thus in touch with the newest phases of physical and chemical investigation, the

countless applications of electricity, the methods of modern engineering, and the practical details of workshop practice, his interest in these things of the world is likely to be quite as broad as that of the average man. His sympathy with research in every branch of science must increase and strengthen as his conception of the great problem of evolution is developed by his own investigations of its earliest phases. And the pleasure and enthusiasm derived from his studies must become, not like the vague passion of the mystic, whose inability to see clearly leads him to pursue strange gods, but such as every successful searcher after truth must experience, whether he deal with the vast dimensions and distances of the heavenly bodies, or with the minute but no less marvelous phenomena of microscopic life and form.

Now, while it cannot be too strongly emphasized that the student of stellar evolution can have no sympathy with the mystic, whose habit of thought must be the very antithesis of his own, yet it is true that the imagination, when properly exercised and controlled, is to be regarded as his best aid to progress. The question of control is so important that it may well be mentioned first. For nothing has done more injury to science than the play of imaginations subject to no control, on the part of men who enjoy in the public press the rank of scientific authorities. Thus great sun-spots become the innocent cause of earthquakes or tornadoes, not to speak of their effect upon the price of wheat. Comets, once the unerring portents of war and pestilence, still carry the brands of conflagration, and threaten at each apparition to destroy the Earth. Mystic properties are ascribed to the center of the universe, and a well-known planet, because it is incorrectly assumed to be stationed there, is dogmatically asserted to be the only possible abode of human life. There is a fine field here for humor and amusing speculation, as the author of the "Moon Hoax," and other more recent writers, have

shown us. But humor is not always intended: the pronunciamentos go forth in the name of science, and are so accepted by a host of intelligent persons, who naturally believe that the supposed authorities have reached their conclusions by scientific methods. Thus there arises a false conception of science, and a popular demand for wonders, which is not easily satisfied by acquaintance with the less sensational facts.

But though dangerous when unrestrained, the imagination, when rightly exercised, is the best guide of the astronomer. His dreams run far ahead of his accomplishments, and his work of today is part of the development of a plan projected years ago. He perceives that only a few generations hence many of the instruments and methods of his time are to be replaced by better ones, and he strains his vision to obtain some glimpse, imperfect though it be, into the obscurities of the future. As he sits in his laboratory, surrounded by lenses and prisms, gratings and mirrors, and the other elementary apparatus of a science that subsists on light, he cannot fail to entertain the alluring thought that the intelligent recognition of some well-known principle of optics might suffice to construct, from these very elements, new instruments of enormous power. He learns of some advance in engineering or in the art of the glass-maker, and dreams of new possibilities in its application to the construction of his telescopes or the equipment of his laboratory. He reads of discoveries in physics or chemistry, and at once his mind is busy in its endeavor to apply the new knowledge to the solution of long-standing cosmical problems.

But here, again, we see the need of control; for with such a multiplicity of interests, and such constant stimulus to the imagination, the danger of mere dilettantism is obvious. With scores of problems suggesting themselves for solution, and with attractions on every hand, each rivaling the other in its apparent possibilities of development, the chief difficulty

is to choose wisely. It is not a question of searching for something to do, but of picking out those things which are most worthy of pursuit. Here the importance of having a definite and logical plan of research becomes apparent. Such a plan may involve a single investigation, continued along systematic lines over a long period of years, or it may comprise several investigations, carried on simultaneously. In a large observatory each piece of work acquires increased importance if it is selected, not at random, or solely because of its intrinsic value, but rather because of the part it plays in a single logical scheme of research. Its intrinsic importance need not be in the least diminished by its relationship to other work, while the illumination which its results cast on the other investigations of the scheme can hardly fail to improve them, and may even reveal the chief source of their meaning. Moreover, the same research, if carried on elsewhere, might prove of small value, in the absence of such suggestions and modifications as are sure to come from the related investigations. We shall have occasion to revert to this question in discussing a plan of attack on the general problem of stellar evolution.

CHAPTER III

THE SUN AS A TYPICAL STAR

BEFORE proceeding to the more detailed portions of our discussion, let us examine the present condition of the bodies with which we are to deal, and briefly trace out those elements of relationship which it will be our purpose later to describe more fully. Let us begin with the consideration of a single object, which we may afterward compare with other objects less easily observed because of their greater distance from the Earth.

The photographic reproduction in Plate II represents the Sun, as seen with an ordinary telescope. So far as could be judged from this picture, the Sun might be described as a luminous sphere, brighter in its central part than near its circumference, and marked with dark spots, irregularly distributed over the surface. On closer examination it will also be seen that there are certain bright regions, which are most easily noticed near the edge of the Sun. The dark spots are the well-known sun-spots, first discovered by Galileo, while the bright regions are the faculae, which have also been known since the invention of the telescope. At times of total eclipse, when the bright body of the Sun is covered by the dark body of the Moon, shielding our atmosphere from the usual brilliant illumination, red flames, sometimes reaching heights of several hundred thousand miles, may be seen rising from a continuous sea of flame, which completely incircles the Sun. These are the prominences, and the continuous mass of flame from which they rise is the chromosphere (Plate III).[1] Extending far beyond these flames into space,

[1] See the remarks on anomalous dispersion, p. 148.

sometimes to a distance of millions of miles, is the corona, which shines with a silvery luster somewhat inferior in brightness to that of the full Moon (Fig. 2, Plate IV).

An analysis of the light of the Sun, made with the spectroscope, has shown the presence of the vapors of iron, sodium, magnesium, calcium, hydrogen, and many other substances known to us on the Earth. In fact, it has been remarked that if the Earth were heated to the temperature of the Sun, the light emitted by its vapors would resemble closely, when analyzed with the spectroscope, the light emitted by the Sun. Thus the chemical composition of the Earth and the Sun is much the same, although we have evidence of the existence in the Sun of a large number of substances not yet found on the Earth. This same means of analysis has led to the discovery that the chromosphere, and the prominences which rise out of it, are composed of the vapor of calcium and of the light gases helium and hydrogen. The sun-spots, too, have also been found to have a characteristic chemical composition; while the corona emits rays which probably indicate the presence in it of very light and tenuous gases.

Observations of the Sun, continued without interruption for more than half a century, have shown that the spots are not constant in number, but vary in a characteristic way in a period of about eleven years. At times of sun-spot maximum the surface of the Sun is marked by large numbers of spots, which are found on attentive observation to be the scene of great activity, and frequently the source of the most violent eruptions. At this period the prominences are large and abundant, and testify to the general condition of disturbance by exhibiting, from time to time, eruptive phenomena on a very large scale, in which great masses of gas have been known to shoot upward with velocities of hundreds of miles a second. With the passage of time these evidences of disturbance and activity become less and less marked, until

finally, during the minimum period, the surface of the Sun for months together may be wholly devoid of sun-spots. The prominences also become less numerous, and eruptive phenomena, so common during the maximum period, are rarely to be observed at the minimum. Even the corona undergoes changes in form which are perfectly characteristic, and show a definite connection with the sun-spot period.

So much for the Sun and its more conspicuous phenomena. We are now led to inquire whether it has any counterparts among the other heavenly bodies. Let us suppose the Sun removed to the distance of the nearest fixed stars. Its light would then be reduced in so great a degree as to be surpassed by that of many of the brighter stars, though it would still remain one of the more conspicuous objects in the heavens. The planets of the solar system would be wholly beyond the range of observation, even with the most powerful telescopes. The light of the Sun would appear yellowish, and it would be impossible to distinguish it from certain stars which also shine with a yellowish light. Spectroscopic analysis of the light of these stars reveals the presence in their atmospheres of elements familiar to us on the Earth; indeed, the chemical composition of some of them can be shown to be practically identical with that of the Sun. On account of its immense distance, the Sun's disk would be reduced to a minute point of light, as in the case of the other stars, and the sun-spots, prominences, corona, and other phenomena would be wholly invisible. For the same reason, such phenomena, though undoubtedly present in other stars, are hidden from observation. We may therefore conclude that the Sun is a star, practically identical in chemical composition and in physical constitution with many other stars in the heavens, and ranking in size below many of these objects.

A very casual acquaintance with the stars, based upon naked-eye observations, is sufficient to make one familiar with the fact that they differ from each other as much in color as they do in brightness. Such objects as *Sirius* shine with a bluish-white light, whereas *Arcturus* is yellowish like the Sun. *Antares*, in the *Scorpion*, is a fine example of a red star, and with the telescope smaller stars may be seen of a deeper red color. Spectroscopic study of these various classes of stars shows in the clearest way definitive peculiarities, which may form the basis of a system of classification. Indeed, we apparently find ourselves in the presence of stars in every stage of growth, from the earliest, as represented by the bluish-white objects, to the latest, typified by the red stars[1] (Fig. 1, Plate IV). Intermediate in point of development are yellowish stars like the Sun.

In various parts of the heavens clusters may be observed, in some of which the stars are widely scattered, as in the *Pleiades*, while in others they are densely packed together, so closely that several thousand stars may sometimes be seen within an area so small that to the naked eye they appear like a single hazy star. Since we find clusters of every degree of density, and since the stars in the heart of some of these clusters are too close together to be separated by the telescope, the question long ago arose whether the nebulae, which seem to resemble luminous clouds in the heavens, are to be regarded as star clusters so dense as to be beyond telescopic resolution. It was not until the spectroscope had been applied by Huggins (see p. 54) that this question was finally settled. It then appeared that some of the nebulae, at least, are vast masses of luminous gas, and that they are therefore not composed of separate stars. It might then be inquired what part in the scheme of evolution such nebulae play. It will be shown in the course of this book that there

[1] See the cautionary remarks on p. 198.

exists between stars and nebulae a relationship so intimate as to leave little doubt that stars are condensed out of nebulae through the long-continued action of gravitation. It thus seems probable that the nebulae represent the stuff from which stars are made, in its primitive and uncondensed state.

CHAPTER IV

LARGE AND SMALL TELESCOPES

It must soon appear, to one who seeks in the heavens with unaided vision for evidences of stellar evolution, that but little progress can be made without powerful instrumental means. When the nature of the problem is considered, and it is remembered that all observations of the stars must be made from the surface of a minute body moving through the midst of the universe, the only cause for surprise will be that instruments of sufficient power for our purpose can be constructed. The distances of the stars are so enormous that it might seem hopeless ever to solve the problem of their physical constitution, or to analyze them as the chemist resolves into its elements a substance in his laboratory.

Let us consider what must be accomplished before we may even begin to study the subject of stellar evolution. In the course of our work we must deal with stars which are not only invisible to the naked eye, but are beyond the reach of any except the most powerful telescopes. We must find the means of collecting the light from such bodies, not only those rays which, if intense enough, could be seen by the eye, but also those which, because of the structure of the eye, are wholly invisible. After collecting together such rays, we must subject them to analysis by instruments which will permit us to draw conclusions, both as to the nature of the chemical elements present in the star's atmosphere and as to the physical condition of these elements, illustrated by the pressure and the temperature to which they are subjected. Although we may never hope to see a star's actual disk, even in the most powerful telescopes of the future, as other

than a minute point of light, we must find means of differentiating one part of the star from another and of determining, for example, whether the vapor of carbon lies above or below that of iron or sodium in its atmosphere. If luminous clouds, like those on the Sun, are strikingly characteristic of the star under observation, we must be able to detect their presence, though we may never see their form. If, as in the case of temporary stars, vast temperatures or pressures may produce great differences in physical condition between the inner and outer parts of a stellar atmosphere, we must learn a way of discovering such differences and of ascribing them to their true cause. Incidentally, and as a necessary precedent to these studies, we must be able to determine whether the star is moving toward or away from the Earth, and to measure its velocity in either direction with great precision.

Moreover, our means of analysis must be so refined that they shall enable us to investigate, not merely the general physical and chemical properties of single stars, but also those minute peculiarities of composition or of motion which may relate them to other stars, and define their precise place in some general scheme of stellar evolution. We must have some means at hand which will bring to light the forms of nebulae, even though they be invisible to a trained eye aided by the most powerful telescope ever constructed. Being given these forms, we must seek for evidences of relationship between the cloudlike nebulae and the stellar points which they surround. And the means of analysis which tells us of the constitution of the stars must also tell us of the nature of the nebulae, thus serving to establish relationships with stars which no mere indications of position or of structure could provide.

A refracting telescope consists of a lens (object-glass) usually mounted at the end of a long tube, which is pointed

at the object to be observed. In the present case we will suppose this to be the Moon. The lens forms an image of the Moon at the lower end of the tube, just as the lens of a camera forms an image on the ground-glass. Indeed, a telescope may be regarded as nothing more or less than a long camera, in which a tube is substituted for the ordinary bellows. By putting a plate at the point where the image is formed, and giving a suitable exposure, the Moon may be photographed, just as a landscape is photographed with the camera. For eye observations, however, the image formed by the telescope is looked at through a small lens called an eye-piece. The image is magnified in the same way, and to the same extent, as any object would be if looked at with the eye-piece, used as an ordinary hand magnifier. The total magnifying power of the telescope, however, of course depends not only upon the magnifying power of the eye-piece, but also upon the size of the image formed by the object-glass. The size of this image is determined solely by the focal length, or distance from the object-glass to the image. Suppose, for example, we have two telescopes, with object-glasses of the same diameter, but of different focal lengths. The one of longer focal length will give the larger image. If the focal length is twice that of the other telescope, the image will be twice as large. With the same eye-piece, therefore, the magnifying power of the longer telescope will be twice that of the shorter one.

We thus see that the size of the image given by a telescope does not depend upon the diameter of its object-glass. The brightness of the image, however, evidently does depend upon the amount of light concentrated in it, and this increases with the diameter of the object-glass. If we double the diameter of the object-glass, we get four times as much light in the image of a star; for the amount of light collected depends upon the area of the object-glass, and this increases as the square of its diameter.

These details are worth remembering, for they determine, in great measure, the relative advantages of large and small telescopes. There is another consideration, however, of the first importance, which must not be overlooked. A small telescope is limited, by the very nature of light, in its power of separating two closely adjacent stars. If these stars are less than a certain distance apart, no increase in the magnifying power of the telescope, either through increase in its focal length or through the use of a more powerful eye-piece, can possibly show them as separate objects. The reason lies in the fact that the image of a star in a telescope is a minute disk, the diameter of the disk depending on the size of the object-glass. The disk grows smaller as the object-glass grows larger; so it is easy to see why a large telescope will divide a close double star when a small one will not: the star images, which are of sensible diameter and consequently overlap, as seen in the small telescope, are reduced by the high resolving power of the large telescope to such minute dimensions that they appear distinct and separate.

Here, perhaps, a word of explanation may be useful; for it is not at first sight obvious that a star should appear *smaller* in a large telescope than in a small one. Such a statement would not be true of the Sun, Moon, or planets. These objects are all comparatively near the Earth, and even a moderate magnifying power will show them (except the most distant planets) as disks on which structural details are visible. The *stars*, however, are so inconceivably remote that no telescope, however powerful, can show their *true* disks. They are mere points of light, brighter, and for this reason apparently larger, in the case of the brilliant stars, but always becoming more minute and pointlike under the most favorable atmospheric conditions and with the most powerful instruments.

The *spurious* disks, which would have no existence if

light-waves were infinitely short, appear large in small telescopes, but small in large ones. In the Yerkes telescope, for example, stars separated by only a tenth of a second of arc can be resolved under the best atmospheric conditions. A four-inch telescope cannot separate stars that are less than a second of arc apart, no matter what magnifying power be applied. In such an instrument, therefore, the thousands of double stars whose components are separated by less than a second appear as single stars. In the same way, minute markings, lying close together on the Sun, Moon, or planets, are not separately distinguished in a small telescope, while in a large one they may be seen as distinct objects, provided the atmospheric conditions are sufficiently favorable.

We may sum up the preceding remarks by saying that in all astronomical observations which involve the separate and distinct recognition of very closely adjacent stars, or a knowledge of the most minute structure of the Sun, Moon, or planets, large telescopes must be employed under excellent atmospheric conditions. Furthermore, if it is a question of collecting sufficient light, either for eye observations, or for photography, or for spectroscopic analysis, from an extremely faint star, the great area of a large object-glass or mirror also becomes essential. Nevertheless it will be shown that for many important investigations small telescopes are equal or even superior to large ones.

This brings us to the much-discussed question of the relative advantages of large and small telescopes, regarding which a great deal has been written. On the one hand, we hear the amusing claims of the promoters of the great telescope which was to be the *clou* of the last Paris Exposition. This immense instrument—which does not seem to have been completed, and is now lying unused—was to bring the Moon within the observer's grasp—if he could reach a meter! The light-heartedness of this claim is manifest when it is

remembered that no existing telescope, under the best atmospheric conditions, has ever shown the Moon as well as it would appear to the unaided eye at a distance of fifty miles.

On the other hand, it has been stated, with great insistence, that it is absurd to use a telescope of more than four inches' aperture east of the Mississippi River, or of more than six inches' aperture in the better atmospheric conditions west of it. This statement, although not so extreme as the one which emanated from Paris, is entirely misleading and unwarranted by the facts. It was probably intended to emphasize a conviction that the atmospheric conditions in the eastern part of the United States are very bad, and unsuited for large telescopes. Now, it is quite true that atmospheric disturbances are the bane of astronomers in all parts of the world; we shall have occasion to discuss this question in a future chapter. It is also true that the meteorological conditions are, on the average, much more favorable for astronomical observations in the southwestern part of the United States than east of the Mississippi River. But it cannot be denied that many of the valuable observations turned out by our eastern observatories are directly due to the fact that they are equipped with large telescopes. That these telescopes would do more and better work under better conditions goes without saying. Most of them would not exist at all, however, if it had been a question of establishing them some thousands of miles from the universities or colleges with which they are connected.

To those who have used both large and small telescopes, the great advantages of large instruments for many kinds of work are well known. I have heard a European astronomer exclaim, when looking at *Jupiter* for the first time with the forty-inch Yerkes telescope, that his years of study of this planet with a small telescope seemed almost useless, so much

more of detail could he perceive at a single glance. I have seen minute structure on the Moon with this telescope, no trace of which could be made out with a twelve-inch telescope on the same evening. Countless fine bright lines in the spectrum of the chromosphere, which could never be detected with the twelve-inch, are easily seen with the forty-inch. Burnham has separated double stars at the theoretical limit of resolution of the Yerkes telescope, and Barnard has observed the tiny fifth satellite of *Jupiter* when it was beyond the reach of all but the largest existing instruments. When I think of these observations and of Ritchey's photographs of the Moon and star clusters, Frost's and Adams' photographs of the spectra of faint stars, and the no less important results obtained by Schlesinger, Parkhurst, Ellerman, Fox, and others with the Yerkes telescope; and when I remember that most of these observations or results could not have been obtained with a small telescope, I see no possible reason for denying the manifold advantages of large instruments. My illustrations have been confined to observations made with the Yerkes telescope, because of personal knowledge of them. But they could be greatly multiplied if the remarkable work of the Lick telescope and of other large instruments were drawn upon for examples. In the next chapter, through the aid of photography, some of the relative advantages of large and small telescopes will be illustrated.

CHAPTER V

ASTRONOMICAL PHOTOGRAPHY WITH CAMERA LENSES

THE emphasis laid in the last chapter on the importance of large telescopes must not be supposed to mean that small telescopes are of little value. The single fact that Burnham discovered 451 new double stars with a six-inch refractor (Plate V) is sufficient evidence to the contrary. It is quite true that small telescopes are not well adapted for certain classes of work, in which large telescopes excel. But their superiority over large telescopes is no less evident in other fields. The equipment of an observatory recognizes this by the provision of both large and small telescopes, each designed for use in the investigations for which it is particularly suited. In fact, the characteristic of a modern astrophysical observatory which distinguishes it most clearly from the old observatory of one or two instruments is the careful adaptation of a multiplicity of special apparatus to certain narrowly defined purposes. The day of the universal instrument has passed, for conditions similar to those which have resulted in the development of the innumerable special tools of the modern machine shop obtain also in the observatory.

The amateur astronomer should keep this fact clearly in mind. There is some reason to fear that the large and expensive equipments of modern observatories have tended to discourage the worker with small instruments. As one who has looked at the subject from both sides, I may be permitted to oppose this pessimistic view. Far from believing that recent developments have been detrimental to the amateur, I am strongly of the opinion that his opportunities for useful work have never before been so numerous. The

importance of this subject, due to the high value of the contributions to astronomy made by amateurs in the past, has led me to devote a subsequent chapter to opportunities for work with inexpensive instruments.

In considering the peculiar advantages of small telescopes in certain fields of research, attention must be called at the outset to the important part played by photography in the astrophysical work of the present day. The photographic plate, through its power of storing up impressions made by feebly luminous rays, has in most cases an immense advantage over the eye. The eye perceives almost at once as much as can be seen by long gazing at a faint object. But the photographic plate continues, hour after hour, and perhaps night after night, to accumulate impressions, so that with sufficiently long exposures, objects far too faint to be seen by the eye with the same telescope are clearly and permanently recorded. Moreover, the photographic plate is sensitive to light-waves which are too short to produce the least effect upon the eye, and in this power of recording objects which otherwise could never be rendered visible, no matter what their intensity of radiation, the plate presents a second great advantage. Because of these and other points of superiority, which far outweigh certain slight defects that in some few instances still leave the plate inferior to the eye, the photographic method is now exclusively employed for many kinds of observations.

Some of the most important results of astronomy have been derived from the use of an ordinary camera, having just such a lens as is found in the possession of thousands of amateur photographers. If we take an ordinary camera and point it on a clear night toward the north pole, it will be found, after an exposure of one or two hours, that the stars which surround the pole have drawn arcs of circles upon the plate (Plate VI). This is due to the fact that

the Earth is rotating upon its axis at such a rate as to cause every star in the sky to appear to travel through a complete circle once in twenty-four hours. Since the pole is the place in the sky toward which the Earth's axis is pointing, it is easy to understand that the nearer the star lies to the pole, the smaller does this circle become. As we move away from the pole we find the curvature of the star trails growing less and less, until at the equator they appear as straight lines.

Just such photographs as these are frequently employed in astrophysical investigations; e. g., for the purpose of recording variations in a star's brightness, which would be shown on the plate by changes in the strength of the trail. But for most purposes it is desirable to have photographs of stars in which they are represented as points of light rather than as lines. To obtain these photographs it is necessary to mount the camera in such a way that it can be turned about an axis parallel to the Earth's axis, at a perfectly uniform rate, once in twenty-four hours. A camera so mounted becomes an equatorial photographic telescope, differing in no important respect, save in the construction of its lens, from the largest refractors.

Here, for example, is a photograph (Plate VII) of the Bruce photographic telescope of the Yerkes Observatory. This instrument has a compound lens ten inches in diameter, made by Brashear from four lenses suitably combined, of such curvature as to form an image at a point only fifty inches distant from the optical center of the lens system. It will be seen that such a lens must produce a very bright and highly concentrated image, in which the various objects are crowded close together because of the small scale of the picture. If the same lens were so constructed as to form an image ten times as far distant from the photographic plate, the several elements of the picture would then be ten times more widely separated, and a longer time would be required

to photograph them, on account of the spreading of the same amount of light over a larger surface. As will be seen from the illustration, the tube which carries the lens and photographic plate is mounted in such a way that it may be turned about an axis parallel to the axis of the Earth by means of a driving-clock, placed in the upper part of the iron supporting column. The same mounting carries not only the ten-inch lens, but also the lens of a guiding telescope, through which the observer watches a star during the entire period of exposure, continued, perhaps, for many hours. He may thus correct any slight irregularity in the motion of the telescope by certain screws provided for the purpose, which permit him to keep the star accurately at the intersection of two illuminated cross-wires. The driving of the clock is so accurate that this is accomplished almost automatically, though small changes in atmospheric refraction and other causes require minute displacements of the instrument to be made from time to time, to insure the perfect immobility of the stellar images upon the photographic plate.

Besides the ten-inch camera and the guiding telescope, the Bruce telescope carries three other cameras, with lenses of 6 inches, 3.4 inches, and 1.6 inches aperture respectively. Thus four photographs of the same part of the heavens, on different scales, determined by the focal lengths of the lenses, are obtained in a single operation. Our knowledge of the structure of the vast girdle of stars that forms the Milky Way is derived in very large part from a study of photographs made with such an instrument. At the Lick Observatory Barnard used the six-inch Willard lens to great advantage in photographing these star clouds, and of late, through the opportunity afforded by the Hooker Expedition at the lower latitude of Mount Wilson, he has carried his work farther south of the celestial equator. The Bruce telescope, temporarily transferred from the Yerkes Observatory to

Mount Wilson for use during the spring and summer of 1905, has yielded some remarkably fine results in Barnard's hands. The smallest of the four photographs made in a single operation is taken with an ordinary "magic-lantern" lens of 1.6 inches aperture and 6.4 inches focal length. This shows a a region about fifteen degrees[1] across within a circular area about 1.7 inches in diameter on the photographic plate. With the ten-inch lens the field of sharply defined images is limited to about eight degrees, but it is still large enough to include extensive star clouds and nebulae. The larger scale, due to the greater focal length of the ten-inch lens, brings out details of structure that are not visible on the smaller photographs. Plates VIII and IX, reduced from the originals in the same proportion, illustrate the relative scales of the photographs made with the two lenses.

The Milky Way, as revealed by such photographs, is a most extraordinary spectacle. The countless stars that compose it are grouped in every conceivable manner, and intertwined with long reaches of diffuse nebulous clouds. Here and there vacant regions, sometimes apparently darker than the background of the heavens, resemble vast lanes, extending through the entire thickness of the star clouds, or perhaps lead one to suspect that an obscuring medium may be cutting off the light from immeasurably distant bodies. Again, a nebula of great extent, diffuse on one side and sharply bounded on the other, may suggest the action of forces beyond our present means of investigation. The filmy veils spread by certain nebulae seem to envelop the stars in mist, though in most cases we cannot say with certainty whether the stars are actually within the clouds, or remote from them in the line of vision. The surest test of relationship between stars and surrounding nebulae is afforded by the spectroscope,

[1] Readers who are not accustomed to angular measure may be reminded that the two "pointers" of the "Dipper" are about five degrees apart.

as will be shown in a subsequent chapter. It has been found that stars of different spectral types, which are ordinarily assumed to indicate different degrees of development, are not equally represented in the Milky Way. The connection between these stars and surrounding nebulae, and the possible relationship between spectral type and the grouping of the stars in the cloudlike forms of the Galaxy, is one of the important problems of the present time. Our knowledge of the Milky Way and its structure is still very meager, but the future is certain to bring great advances.

These illustrations may suffice to show the uses of the ordinary camera lens in investigations bearing upon the general structure of the Milky Way. A simple comparison will serve to bring out both the advantages and disadvantages of large telescopes in studies of a similar kind. Plate X shows the Milky Way in *Ophiucus* from one of Barnard's photographs made with a portrait lens. It affords a superb picture of this part of the sky, such as no visual observations with any telescope could supply. If the same region of the heavens were examined with a large telescope, the field of view would be so restricted that no proper impression could be obtained as to the character of the Milky Way or the distribution of the stars within it. It would, of course, be possible to count one by one the hundreds of stars included within a single field of view, and by long and laborious measurements to map these stars and ultimately to build up, from combination into a single picture of the results thus obtained, a representation of the Milky Way. However, such a task would occupy years of labor, and the result would be less valuable, for many purposes, than that illustrated in Plate X. This picture is an autographic record, showing not only the distribution of the stars, but also their relative brightness on the date of the exposure.

Since such results are due to photography, the comparative value of large telescopes should be judged by the same means. Plate XI is a reproduction of a photograph of the cluster *Messier* 11, which is represented in Plate VIII as a small circular white dot in the upper part of the picture. The short focal length of the camera lens, which causes it to form upon the plate a small-scale picture covering a large region in the heavens, is not competent to separate out the single stars of this cluster. The photograph reproduced in Plate XI was made by Ritchey with the forty-inch Yerkes telescope, which has a focal length of sixty-four feet, as compared with the focal length of 6.4 inches of the camera lens used for Barnard's photograph. The scale of the negative obtained with the Yerkes telescope is therefore about 120 times as great as in the case of the camera lens. This great scale, while disadvantageous so far as it bears upon the question of the general structure of the Milky Way, would be in the highest degree advantageous if the problem under consideration involved the study of the individual stars in the cluster *Messier* 11. With the camera lens these stars are so close together upon the plate that their separate images are confused. With the Yerkes telescope the images are widely separated from one another, permitting the position and the brightness of each star to be determined with great precision. The Bruce lens gives an intermediate scale. If Plate IX had been enlarged in the same proportion as Plate XI, this cluster would be shown fairly well resolved. But *Messier* 13 (Plate XIX) is far beyond the capacity of the Bruce lens.

It may be of interest to include here another photograph illustrative of the advantages of great focal length for certain classes of work. Plate XII represents a photograph of the Moon, made by Ritchey with the twelve-inch Kenwood telescope, which is eighteen feet long. This picture gives an

excellent general idea of the lunar topography. But if the detailed structure of the lunar mountains is to be investigated, such a picture as that reproduced in Plate XIII would evidently be far more effective for the purpose. *Theophilus*, the great ring mountain here represented, may be seen in Plate XII on a smaller scale. The large-scale picture was obtained by Ritchey with the forty-inch telescope, which, as already remarked, has a focal length of sixty-four feet. The scale of the original photograph was therefore about three and one-half times as great as that of the photograph taken with the Kenwood telescope. In consequence of the larger scale of the Yerkes picture, it brings out many small details which are entirely lacking on the Kenwood photograph.

These illustrations of the separating power of the large telescope may lead us to an examination of the instrument itself (Plate XIV). Although so much larger, it differs in no essential particulars from the Bruce photographic telescope, also made by the firm of Warner & Swasey. The great weight of the forty-inch lens, amounting with its cell to half a ton, requires that the tube which carries it shall be of immense rigidity and strength. This tube, sixty-four feet in length, is supported at its middle point by the declination axis, which in its turn is carried by the polar axis, adjusted to accurate parallelism with the axis of the Earth. By means of driving mechanism in the upper section of the iron column, the whole instrument is turned about this polar axis at such a rate that it would complete one revolution in twenty-four hours. Although the moving parts weigh over twenty tons, the telescope can be directed to any part of the sky by hand, but this operation is much facilitated by the use of electric motors provided for the purpose. When once directed toward the object to be observed, it will frequently happen that the lower end of the telescope is far out of reach above the observer's head. For this reason the

entire floor of the observing-room, seventy-five feet in diameter, is constructed like an electric elevator, which, by moving a lever, can be made to rise or fall through a distance of twenty-three feet. Thus the lower end of the telescope is rendered accessible even when the object is near the horizon (Plate XV). In order that the observing slit may be directed to any part of the sky, the dome, ninety feet in diameter (Plate XVI), is mounted on wheels and can be turned to any desired position by means of an electric motor controlled from the rising-floor.

The telescope is used for a great variety of purposes in conjunction with appropriate instruments, which are attached to the lower end of the tube near the point where the image is formed. We have already examined a photograph of a star cluster taken with this telescope, but without describing the process of making it. As a matter of fact, the forty-inch object-glass was designed for visual observations, and its maker, the late Alvan G. Clark, had no idea that it would ever be employed for photography. Without dwelling upon the distinguishing features of visual and photographic lenses, it may be said that the former are so designed by the optician as to unite into an image those rays of light, particularly the yellow and the green, to which the eye is most sensitive. With the only varieties of optical glass obtainable in large pieces, it is impossible to unite into a single clearly defined image all of the red, the yellow, the green, the blue, and the violet rays that reach us from a star. Therefore, when the optician decides to produce an image most suitable for eye observations, he deliberately discards the blue and violet rays, simply because they are less important to the eye than the yellow and green rays. For this reason the image of a star produced by a large visual refracting telescope is surrounded by a blue halo, containing the rays discarded by the optician. These very rays, however, are the ones to which

the ordinary photographic plate is most sensitive; hence in a photographic telescope the blue and violet rays are united, while the yellow and green rays are discarded.

The forty-inch telescope is of the first type, constructed primarily for visual observations. In order to adapt it for photography, Ritchey, then a member of the Yerkes Observatory staff, simply placed before the (isochromatic) plate a thin screen of yellow glass, which cuts out the blue rays, but allows the yellow and green rays to pass. As isochromatic plates are sensitive to yellow and green light, there is no difficulty in securing an image with the rays which the object-glass unites into a perfect image. During the entire time of the exposure some star lying just outside the region to be photographed is observed through an eye-piece magnifying 1,000 diameters. This eye-piece is attached to the frame which carries the photographic plate, and is susceptible of motion in two directions at right angles to one another (Plate XVII). In the center of the eye-piece are two very fine cross-lines of spider web, illuminated by a small incandescent lamp. If the observer notices that through some slight irregularity in the motion of the telescope, or some change of refraction in the Earth's atmosphere, the star image is moving away from the point of intersection of the cross-lines, he instantly brings it back by one or both of the screws. As the plate moves with the eye-piece, it is evident that this method furnishes a means of keeping the star images exactly at the same position on the plate throughout the entire exposure.

Many other comparisons of large and small telescopes might be given, and some of these will be included in subsequent chapters. They all serve to demonstrate that each telescope has advantages and disadvantages peculiar to its size and type of construction. For some purposes small camera lenses are to be preferred to all other instruments.

In fact, without their aid many investigations of the highest importance could never be undertaken. For other investigations these short-focus instruments may be entirely unsuited, while refracting telescopes of great focal length may give excellent results. These larger telescopes also have their limitations, and must yield to reflecting telescopes in certain other kinds of work. The truth of this statement will be brought out in the next chapter.

CHAPTER VI

DEVELOPMENT OF THE REFLECTING TELESCOPE

On a night in April, 1845, while sweeping the sky in the constellation of the *Hunting Dogs*, the observers with the great Parsonstown reflector discovered a spiral nebula. The instrument with which the discovery was made may well be regarded as one of the most remarkable scientific achievements of the nineteenth century. With its immense mirror, six feet in diameter, having a focal length of fifty-four feet, the great telescope of Lord Rosse surpassed in size all others ever constructed. Unfortunately for the progress of science, the engineering methods of that day were inadeqnate to provide a suitable mounting for this gigantic instrument. All parts of the machinery had to be constructed on the spot, with such tools as the period and the circumstances afforded. It is no small credit to the Earl of Rosse that under these conditions the telescope was ever erected, and kept in active use by an able company of observers. Supported upon a ball-and-socket joint at its lower end, the enormous tube, swung in chains, was confined to observations within a short distance of the meridian by two flanking stone walls. The observer, mounted upon a platform far above the ground, saw the image of an object as he looked down into the tube. To the present-day astronomer, provided with every appliance to facilitate the finding of an object, and with an accurate driving-clock which moves the telescope so steadily and uniformly as to maintain the image in the field of view for hours together, it is little short of marvelous that the observers with the great Parsonstown reflector were able to obtain results of value. But, in spite of the difficulties to be over-

come, both in manipulating the telescope and in finding opportunities for observation under the cloudy skies of Ireland, Lord Rosse and his assistants recorded many valuable discoveries in their memoirs. Of all these discoveries that of the spiral nebula in *Canes Venatici* was perhaps the most significant of the future (Plate LXXXVIII). Before this chapter is concluded we shall see how this beautiful object, which once stood alone among the heavenly bodies as the only visible representative of a distinctly spiral form, has now come to be regarded, through the work of Keeler, as a type of the most interesting and the most numerous class of nebulae.

The history of the Parsonstown reflector has in some degree resembled that of almost every reflecting telescope ever built. The infinite care expended by Herschel and by others who have followed him in the construction of mirrors for such instruments has been in large part annulled by the imperfections of the mountings provided for the mirrors. In the period that preceded the introduction of photographic methods, these imperfections were far less serious than they would be considered from our present point of view. It is true that they hampered observation, and in the early days rendered accurate measurement with the telescope practically impossible. But the employment of the photographic plate has imposed a new condition, rigorous and unyielding, upon the constructors of telescope mountings. In order to secure satisfactory photographs, which shall do full justice to the optical qualities of the instrument, and show only such defects as atmospheric disturbances may produce, it is necessary that the mirrors be so rigidly supported, and so accurately moved by the driving-clock, that a stellar image shall not depart, during exposures of many hours, by so much as one-thousandth of an inch from a fixed position upon the photographic plate.

In view of the difficulties to be overcome, it will be understood that to accomplish such a result is no small task. In the first place, the mirror, which is so sensitive to deformation that it will bend under its own weight unless supported by special apparatus, must be firmly mounted, yet without strain, at the lower end of an open tube. In the second place, protection must be provided against currents of warm and cold air, and even against the heat radiated from the observer's body, on account of the great sensitiveness of the mirror to heat, and of the light-rays to irregular refraction in the telescope tube. These precautions having been taken, the tube must be so mounted that it can be moved with perfect steadiness and uniformity about an axis parallel to the axis of the Earth. This condition is imposed by the necessity of counteracting the apparent motion of the star through the heavens, due to the rotation of the Earth. But while this rotation is uniform, the motion of the star is not, since the displacement of its apparent position from its true position in the heavens, due to the bending of its rays during transmission through the Earth's atmosphere, varies with the height of the star above the horizon. It therefore becomes necessary, as previously explained, to supplement the uniform motion of the driving-clock by corrections, accomplished by the hands of an observer. All these obstacles having been surmounted, there still remain serious sources of difficulty in the shaking of the telescope by the wind, the changes of temperature during the exposure, which alter the focal length of the mirror, and finally, most serious of all, disturbances in the atmosphere which tend to blur and confuse the image, instead of leaving it, sharp and well defined, to make its record upon the photographic plate. It should also be remembered that the observer must be prepared to hold his eye at the eye-piece, and correct every few seconds the position of the plate, throughout exposures lasting several hours,

in an open dome where the temperature may not infrequently be below zero.

After the erection of Lord Rosse's great reflector, the attention of opticians was confined mainly to the construction of refracting telescopes, which grew rapidly in size, reaching apertures of fifteen inches in the Harvard refractor (1845), thirty-six inches in the Lick refractor (1889), and forty inches in the Yerkes refractor (1897). In these instruments careful attention was given to all details of mechanical construction, and the Lick and Yerkes telescopes are among the most successful products of modern engineering.

The development of the reflecting telescope has been due mainly to amateurs, whereas refractors have been made by professional opticians and mounted by experienced engineers. To the inadequate equipment of the amateur's workshop may therefore be ascribed many of the deficiencies in the mountings of reflecting telescopes. In some cases, however, reflectors of large aperture, figured and mounted by professional opticians and engineers, have given results of little or no value. In these cases, as in others, it appears that insufficient attention was paid to the excessive sensitiveness of large mirrors, which causes them to require much more careful treatment than is amply sufficient to yield good images with a lens.

In stellar spectroscopic work good results were obtained with reflectors by Huggins and Draper at a comparatively early period, but it was not until the last years of the nineteenth century that such telescopes were employed with any considerable degree of success for the photography of nebulae. The first photograph of a nebula was obtained with a refracting telescope by Draper in 1881. Photographs of the Great Nebula in *Andromeda*, made by Roberts in 1886 with a twenty-inch reflector, showed for the first time the truly spiral form of this remarkable object, and thus indicated

some of the great possibilities of investigating nebular structure with instruments of this type. Briefly speaking, their superiority to refractors lies in the fact that the light is not weakened by passage through glass, but, after reflection from a surface of pure silver, all the rays, independently of their color, are united in a common focus. With a refractor many of the rays are completely cut off during transmission through the glass of the lens, which is as impervious as so much steel to the very short waves of the ultra-violet spectrum. Furthermore, a lens does not unite all the rays of different colors into a single focus, but forms a series of images, corresponding to light of different wave-lengths. In order to get a sharp photograph with a refracting telescope, it is therefore necessary to discard some of these rays, in the manner already described (p. 35). The reflector, on the contrary, utilizes all of the light[1]—an advantage which is clearly shown by the results obtained with this type of telescope.

The photographic studies of nebulae made by Keeler with the Crossley reflector of the Lick Observatory, mark a step of the greatest importance in the development of the reflecting telescope. The mounting of this instrument, constructed in England some years previously, and presented to the Lick Observatory by Mr. Crossley, was very poorly adapted to carry the excellent mirror of three feet aperture. But through the extraordinary efforts of Keeler, whose severe exertions in carrying out this work hastened his death, the mounting was so strengthened and improved as to permit remarkable results to be obtained. In other hands, even after these improvements had been made, it is doubtful whether such exquisite photographs would have resulted. But, after many unsuccessful efforts, Keeler learned how to overcome the difficulties peculiar to the instrument, and in this he has been

[1] Except a certain percentage lost in reflection.

ably followed by Perrine.[1] We shall have occasion later to refer to their results.

The mounting of the two-foot reflecting telescope of the Yerkes Observatory was designed expressly for photographic purposes, and no pains were spared to adapt the instrument for the exacting requirements of such work. The mirror, $23\frac{1}{2}$ inches in diameter and of 93 inches focal length, was constructed by Ritchey in 1895 at his home in Chicago. This mirror is of the highest quality, meeting the most severe optical tests that can be applied to it. The mounting of the telescope, designed by Wadsworth, with modifications by Ritchey, was constructed in the instrument shop of the Yerkes Observatory, and is very heavy and rigid. In the photograph (Plate XVIII) the mirror may be seen in position at the lower end of the skeleton tube. At the upper end of this tube is a small plane mirror, so supported that its face makes an angle of 45° with the axis of the tube. The telescope is therefore of the Newtonian type, the image being formed on the photographic plate near the upper end of the tube, after reflection of the cone of rays from the small mirror. The double slide plate-carrier, which holds a plate $3\frac{1}{4} \times 4\frac{1}{4}$ inches in size, is precisely similar to the plate-carrier employed with the forty-inch refractor (Plate XVII).

A comparison of the results obtained with this instrument, with those secured with the forty-inch Yerkes refractor, will suffice to show the peculiar advantages of the reflector for certain kinds of work. It should not be forgotten that the forty-inch refractor has other advantages, which fit it for work that could not be done under any circumstances with the two-foot reflector.[2] But in the photography of faint

[1] A new and satisfactory mounting has since been constructed for the Crossley reflector.

[2] For example, the scale of the images given by the forty-inch is eight times that of the two-foot reflector. Moreover, the former is well adapted for work on the Sun, for which the latter cannot be used.

stars, particularly in the photography of nebulae, the two-foot reflector is especially useful. It is possible with this instrument, in an exposure of only forty minutes, to photograph stars which are at the extreme limit of vision with the forty-inch refractor. With longer exposures, countless stars, which can never be seen or photographed with the large refractor, are recorded on the plates. Compare, for example, the photographs of the star cluster *Messier* 13, reproduced in Plates XIX and XX. The principal advantage of the reflector in such work, as already explained, is the concentration of the light-rays, irrespective of their color, in a single focal image.

The photographs of nebulae obtained by Ritchey with the two-foot reflector show in a remarkable way the beauty and delicacy of structure which characterize these objects. It will be seen from the illustrations in the plates that the nebulae are of many types, although the spiral form predominates. The Great Nebula in *Orion* (Plate XXI), which is the most brilliant of the larger nebulae, is of irregular form, and marked complexity of structure. Of very different pattern is the beautiful nebula in *Cygnus*, the delicate filamentous structure of which is admirably shown by Ritchey's photograph (Plate LXXXVII). In the nebulae which envelop the stars of the *Pleiades* (Plate LXXXVI) two very different types of structure are shown; long parallel filaments predominate, but there may also be seen in the photograph a mass of nebulosity resembling the flame of a torch blown by the wind. But although, as we shall see, evidences may be found of the relationship of the stars in these nebulae to the cloud-forms themselves, the spiral nebulae certainly appeal most strongly to the imagination. The largest of these, the Great Nebula in *Andromeda*, is perhaps the most interesting object in the heavens (Frontispiece). Persistent attempts to measure the distance of this nebula from the Earth, made with the most

powerful of modern instruments, have totally failed. We may therefore conclude that this distance is almost inconceivably great, and that therefore the dimensions of the nebula are so enormous as to be quite beyond comparison with those of the solar system. In the beautifully defined spiral character of this object, so clearly visible on the photograph, although beyond recognition in visual observations, we seem to see strong indications of motion with respect to the center. But hitherto, in spite of the careful comparison of photographs made many years apart, no evidence of such motion has been detected. This fact would tend to confirm what we already know from measurement, namely, that the nebula is exceedingly remote from the Earth, and that the phenomena which it exhibits are on a gigantic scale. We cannot doubt that the component parts are in motion, and that in the course of time evidences of this motion will come to light. But to detect them it is certain that the most powerful instrumental means will be required, and that long intervals of time must separate the photographs which are to be compared.

The Great Nebula in *Andromeda* thus stands as the largest representative of that great class of nebulae which was first made known through Lord Rosse's discovery of the spiral nebula in the *Hunting Dogs*. From some of Ritchey's photographs we are fortunate in being able to illustrate other spiral nebulae, which differ in various particulars, but in all cases show clearly the spiral structure (Plates LXXXIX and XC). As already stated, Keeler's photographic investigations with the Crossley reflector have shown that while large objects of this kind are comparatively few, the sky is scattered over with an immense number of small ones. The investigation of these nebulae, with the great reflecting telescopes of the future, should lead to results of fundamental importance.

CHAPTER VII

ELEMENTARY PRINCIPLES OF SPECTRUM ANALYSIS

THE problem of determining the nature of the nebulae seemed to be placed beyond solution by telescopic means when it was found that star clusters exist in which the stars are so densely packed that they cannot be separately distinguished by any telescope. A photographic illustration of this is given in Plate XIX. In Plate XI we see a cluster easily resolved into its constituent stars. In the case of *Messier* 13, however, the photograph here reproduced might leave some doubt on the score of resolvability.[1] Visual observations, better competent than photographic ones to settle this particular point, remove the doubt in the present instance. But other clusters are still more closely crowded, and it was easy to believe that the unresolved nebulae might be objects of this nature. The structure of such a nebula as that shown in Plate XC might also be supposed to favor such a view. Sir William Herschel, great not only as an observer, but as a philosopher who looked deep into the nature of things, was not deceived by these circumstances, and persisted in his belief that the nebulae are masses of uncondensed gas, differing essentially from clusters of stars. As evidence of the uncertainty which nevertheless existed, it must be added that Sir John Herschel, though himself a great philosopher, was led to a contrary conclusion. For him no nebula existed that could not be resolved with a sufficiently powerful telescope into a congeries of stars. Under these circumstances it is evident that some additional means of analysis must be called upon to solve the problem. For as telescopes increased in size the nebulae remained unresolved, showing that either they were in their

[1] Even the large-scale photograph in Plate XX does not separate the closest stars.

nature unresolvable, or that far more powerful instruments would be required to reveal their constituent parts.

This was the condition of affairs when Spencer boldly took issue with the astronomers. Convinced that the principle of evolution must operate universally, and that the stars must have their origin in the still unformed masses of the nebulae, he ventured to question the conclusion that the resolution of nebulae into stars was only a matter of telescopic power. He had not long to wait for support, for at this juncture a new method of research, long previously foreshadowed by Fraunhofer's analysis of sunlight in the early part of the nineteenth century, suddenly proclaimed its power of accomplishing many surprising results.

It has been known since the time of Newton that when sunlight is passed through a prism, it is spread out into a band containing all the colors of the rainbow. In Newton's experiments the sunlight was admitted to the prism through a circular hole, and he consequently failed to see in the colored spectrum any of those breaks or dark lines that were found in later years to be so significant. Fraunhofer, on the contrary, examined sunlight which reached the prism from a narrow slit, placed at a considerable distance. He was rewarded by the discovery of a large number of dark lines, differing greatly from one another in intensity, and irregularly distributed through the spectrum. He measured the positions of these lines in the spectrum with care, and designated the more striking ones with the letters of the alphabet. His designations are still retained, and the dark lines of the solar spectrum are still called the Fraunhofer lines. But of the origin of these lines Fraunhofer had no knowledge. He found, indeed, that the lines seen in sunlight, while present in the light of the planets, were replaced by different lines in the spectra of some of the stars. But while he concluded that the cause of the lines did not reside in the

Earth's atmosphere, he nevertheless failed to discover their true explanation, and thus did not perceive the possibilities of the science of spectrum analysis.

Let us consider for a moment what happens when light is passed through a prism. We may assume the light to be derived from the glowing filament of an incandescent lamp, placed just in front of a narrow slit. After passing through the slit *a* (Fig. 1) the divergent rays fall upon the lens *b*,

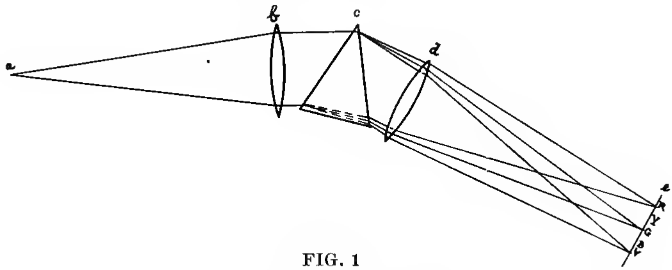


FIG. 1
Passage of Rays through a Prism

which renders them parallel, and is known as the collimating lens. The parallel rays now meet the face of the prism *c*, through which they are transmitted. After passing through the prism the rays fall upon the lens *d*, precisely similar to the collimating lens, which forms an image on the screen *e*.

Now, when light strikes a prism it is deviated from a straight path, and the amount of its deviation depends upon the color of the light. Yellow light, for example, is deflected by a prism more than red light. Green light is deflected more than yellow light, blue light suffers even a greater change of direction, while violet light is deflected most of all. It is thus evident that if the light from the incandescent lamp were pure red, and contained no other color, we should have a red image of the slit at *R*. If it were yellow, a yellow image of the slit would be formed at *Y*. Green light would form a green image of the slit at *G*, blue light a blue image

at *B*, and violet light a violet image at *V*. White light is compounded of all these colors, and shows every intermediate gradation of tint. When passed through a prism it is therefore dispersed into a colored spectrum, extending from red at one end through yellow, green, and blue to violet. This is called a *continuous* spectrum, and is produced when the light from any white-hot solid body is analyzed by a prism. Liquids, or even gases when sufficiently compressed, may give a continuous spectrum when highly heated. But vapors and gases, under ordinary conditions, produce characteristic spectra of bright lines, by which they may be recognized.

For example, let us replace the incandescent lamp flame by a non-luminous gas flame, such as is produced when gas is burned after being thoroughly mixed with air. If we introduce into this flame a little common salt, it will be instantly colored a deep yellow. This yellow light, after transmission through the slit and the prism, will produce upon the screen a single yellow line at the point *Y*. A more powerful instrument would resolve this line into two, placed very close together on the screen. But for our present purposes we may consider this to be a single line due to the metal sodium, which in conjunction with chlorine constitutes common salt. Wherever sodium is present in a state of vapor, whether in a flame, or between the carbon poles of an electric arc, or in the atmosphere of the Sun, or in that of the most distant star, it gives rise to this line, which always lies at precisely the same point in the spectrum. With sufficiently powerful instruments the line is always double, and its presence, when accurately determined, is sufficient to prove the existence of sodium in any luminous source (Fig. 1, Plate XXII).

Most substances, when their vapors are caused to radiate in this way, produce more than one colored image of the slit upon the screen. Thus strontium, when introduced into

the flame, gives two red lines and a strong blue line. Potassium gives a line in the extreme red and another in the extreme violet. But the essential point to notice is that no two substances give lines at precisely the same place in the spectrum. From this we may conclude that the spectra are entirely characteristic of the various elements, and therefore that the presence of these elements in a state of vapor can always be recognized by the detection of their peculiar lines.

The spectra of the elements are of all degrees of complexity, ranging from only two or three lines up to several thousand. Iron, for example, when turned into vapor in the electric arc, shows, after analysis by the prism, several thousand lines, irregularly distributed through all parts of the spectrum (a few of these are shown in Fig. 2, Plate XXII). It is evident, therefore, if the lines are to be clearly distinguished from one another, and so accurately recognized as to avoid confusing a line of iron, for example, with one belonging to some other substance, that powerful dispersion may be necessary; i. e., the various lines must be separated from one another as far as possible by drawing out the spectrum to a great length. This can be done by passing the light through several prisms in succession, rather than through a single prism, as in the present instance.

So far we have referred to the spectra of metallic vapors, rendered luminous in the gas flame or in the electric arc. In order to obtain the characteristic spectrum of a gas, such as hydrogen, it may be placed in a tube, and made luminous by an electric discharge. The best results are obtained after the pressure in the tube has been reduced by pumping out some of the gas, until the electric discharge passes quietly and continuously, so that the whole interior of the tube continues to glow with the light of its gaseous contents. This light, when analyzed by a spectroscope like that shown in Fig. 2. is found to give lines which are character-

istic of the gas employed. The light of hydrogen in a vacuum tube, for example, gives precisely the same spectrum as the light of hydrogen proceeding from one of the great flames at the edge of the Sun.

We have now considered two types of spectra: (1) the *continuous* spectrum, produced when a solid body, a liquid, or

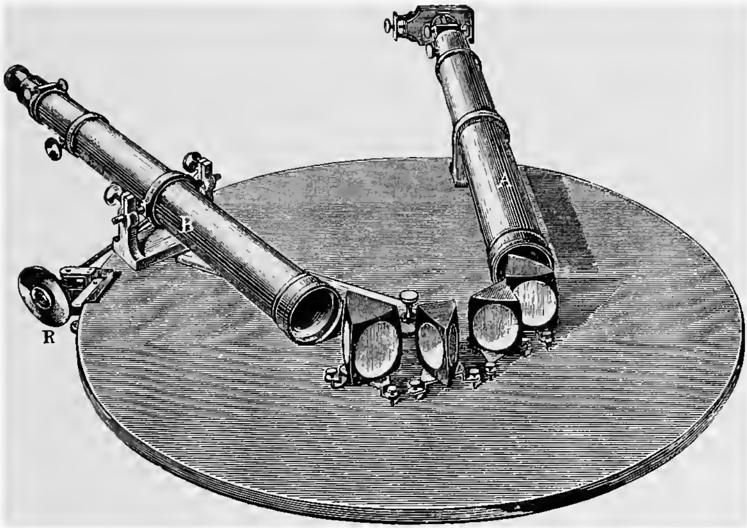


FIG. 2
Kirchhoff's Spectroscope

a highly compressed gas, is rendered white-hot by sufficient heat; and (2) a *bright-line spectrum*, consisting of bright lines, irregularly distributed on a dark background, and derived from the prismatic analysis of the light emitted by luminous metallic vapors, or gases rendered incandescent by electric discharges. One other type of spectrum remains to be mentioned: a *dark-line spectrum*, such as Kirchhoff observed and explained when he effected his famous analysis of sunlight at Heidelberg in 1859.

We have already remarked that Fraunhofer had noted

the existence of dark lines in the continuous spectrum of the Sun, and accurately measured their positions, though without understanding their meaning. Kirchhoff, using the four-prism spectroscope shown in Fig. 2, saw these same dark lines in the solar spectrum, and succeeded in explaining their origin. In the yellow part of the spectrum he observed two strong dark lines, very close together. When the sunlight was excluded from the spectroscope, and a gas flame containing sodium vapor was placed in front of the slit, two strong bright lines, occupying exactly the same positions as the dark lines of the solar spectrum, were seen in their place. The flame was then copiously charged with sodium vapor and retained in its position in front of the slit, the sunlight being permitted to shine through it. It was immediately noticed that the two dark lines in the solar spectrum were considerably darker and more conspicuous when the sunlight passed through the sodium flame than when it was observed alone. Furthermore, it was found that when any white light, producing a continuous spectrum without lines, was allowed to shine through a flame containing sodium vapor, the effect of the flame was to produce two dark lines in the yellow, in the precise position of this conspicuous pair of dark lines.

Iron, when transformed to luminous vapor in the electric arc, gave an even more convincing proof that the true explanation of the solar spectrum had been found: the bright lines observed in its spectrum by Kirchhoff and Bunsen were seen to be represented in the solar spectrum by an equal number of dark lines, precisely resembling them both in position and in relative intensity. Magnesium, nickel, calcium, and other substances gave similar results, and the conclusion was irresistible that all of these substances exist in the Sun in a state of vapor. It followed from these experiments that the body of the Sun must be an intensely hot mass, emitting white light, which, if it could be observed

alone, would give a continuous spectrum, crossed by no lines of any kind. Surrounding this brilliant white sphere, the observations proved the existence of a cooler atmosphere containing, in a state of vapor, most of the metals known on the Earth. These vapors, though cooler than the central body of the Sun, are nevertheless intensely hot, their temperature undoubtedly exceeding that of the most powerful electric arc. Hence, if their light could be observed alone, they would be seen to give a very complex spectrum of bright lines, in which all of the lines characteristic of the different elements would be present. It will be shown later that such a spectrum of bright lines may be seen at the edge of the Sun, when the apparatus is so adjusted as to admit only the light of the chromosphere to the slit of the spectroscope, while excluding all of the light from the Sun's disk. The bright lines in this spectrum are less brilliant than the continuous spectrum due to the more highly heated body of the Sun. Hence, when observed against the disk, the bright lines, appear dark by comparison. The cooler metallic vapors were shown by Kirchhoff's experiments to be capable of *absorbing* the same rays which they themselves emit, and the feebler radiations, emitted by the vapors themselves, produce the dark lines of the solar spectrum.[1] It is important to notice that these so-called dark lines are dark only by comparison, since it will be explained later that photographs of the Sun can be taken by the light of any of these lines with the spectroheliograph, showing the distribution of the corresponding element in the solar atmosphere.

It immediately became evident to students of astrophysics that the method of analysis initiated by Kirchhoff must prove immensely powerful in extending their researches. In 1862 Huggins, Secchi, and Rutherfurd commenced their extensive

[1] In Fig. 1, Plate XXII, the two bright lines are due to very hot sodium vapor at the center of the arc. The cooler and less dense vapor in the outer arc produces, by absorption, the narrow dark lines seen superposed on the bright ones.

observations on the spectra of stars, and soon established a system of types, based upon the examination of the spectra of several thousand objects. This work has since been greatly extended through the application of photographic methods, introduced by Huggins, and applied with marked success by Draper and many others. In 1868 the spectroscope was used for the first time to analyze the red flames seen during total eclipses of the Sun. Not only did it demonstrate their gaseous nature, but a short time later, through the efforts of Janssen, Lockyer, and Huggins, it was found possible to employ the spectroscope to observe the forms of the prominences in full sunlight.

These and other applications of the spectroscope will be more fully described in subsequent chapters. Our present purpose is to explain how the new method, in the hands of Huggins (Plate XXIII), finally proved beyond doubt that certain nebulae are to be sharply distinguished from star clusters.

Sir William Huggins' account of his first spectroscopic examination of a nebula is recorded in the *Publications of the Tulse Hill Observatory*, Vol. I:

On the evening of August 29, 1864, I directed the spectroscope for the first time to a planetary nebula in *Draco*. I looked into the spectroscope. No spectrum such as I had expected! A single bright line only! At first I suspected some displacement of the prism and that I was looking at a reflection of the illuminated slit from one of its faces. This thought was scarcely more than momentary; then the true interpretation flashed upon me. The light of the nebula was monochromatic, and so, unlike any other light I had as yet subjected to prismatic examination, could not be extended out to form a complete spectrum. After passing through the two prisms it remained concentrated into a single bright line, having a width corresponding to the width of the slit, and occupying in the instrument a position at that part of the spectrum to which its light belongs in refrangibility. A little closer looking showed two other bright lines on the side toward the blue, all three

lines being separated by intervals relatively dark. The riddle of the nebulae was solved. The answer, which had come to us in the light itself, read: Not an aggregation of stars, but a luminous gas.

With this advance a new era of progress began. The power of the spectroscope to distinguish between a glowing gas and a starlike mass of partially condensed vapors established it at once in the place it still holds as the chief instrument of the student of stellar evolution. It became apparent that the unformed nebulae might furnish the material from which stars are made.

It must not be forgotten, however, that only a small number of nebulae give a spectrum of bright lines, showing them to be gaseous. Most of the nebulae, including the very numerous spiral type, have a continuous spectrum, in which no lines have yet been detected. As stars are almost certainly formed from these "white" nebulae, as well as from the "green" gaseous ones, the theory of stellar evolution must be broad enough to embrace both types.

CHAPTER VIII

GRATING SPECTROSCOPES AND THE CHEMICAL COMPOSITION OF THE SUN

THE general process employed by Kirchhoff to investigate the chemical constitution of the Sun has already been described, but it also seems desirable to give an account of the perfected method used for this purpose in a modern laboratory. In order to prove that a given substance exists in the Sun, its lines must be identified with certainty in the solar spectrum. The spectrum of iron, for example, contains thousands of lines, and it might easily happen that through chance proximity many of these lines would appear to coincide with some of the exceedingly numerous lines of the solar spectrum. It is evident, therefore, that the method of comparison adopted must be such as to permit of a high degree of precision in measuring the positions of the lines. In other words, the dispersion of the spectroscope must be so great as to give a very long spectrum, in which the lines are well separated from one another. Thus their positions can be accurately determined, and there is no danger of confusion in the case of closely adjacent lines, which in a less powerful instrument might be seen as one.

The recent great advances in spectroscopy have been due in very large measure to the success of Rowland in ruling gratings of high resolving power. In a previous chapter it was remarked that the dispersion of a spectroscope may be increased by increasing the number of prisms through which the light passes. This not only gives a longer spectrum; it also increases the resolving power of the instrument, or its capacity of separating closely adjacent lines. But

through the loss of light by reflection and absorption, which becomes very serious when many prisms are employed, a limit is soon set to the increase in resolving power of prism spectroscopes. It is for this reason that the grating has played so large a part in the recent development of the subject. For the resolving power of a perfect grating depends only upon the total number of lines it contains, and the light efficiency, per unit area, may be as great for a large grating as for a small one.

The production of very powerful spectroscopes, through the use of large and accurately ruled gratings, is what Rowland succeeded in accomplishing in his epoch-making work at the Johns Hopkins University. An optical grating consists of a polished metallic surface, on which many equidistant lines are ruled with a diamond point. The perfection of the spectra given by such a grating depends upon the number of lines it contains and upon the accuracy of their spacing. The difficulty of Rowland's task will be appreciated when it is remembered that a grating must contain from 10,000 to 20,000 lines per inch, and that errors in the positions of the lines, amounting to a very small fraction of the interval between them, would affect the performance of the grating, tending to blur and confuse the spectra produced by it.

Gratings that gave very good results were made many years ago by Rutherfurd, of New York, but it remained for Rowland to surpass them, both in quality and in size. His celebrated ruling-engines (Plate XXIV), which are still in regular use in the underground constant-temperature vaults of the physical laboratory at the Johns Hopkins University, depend for their success upon the fact that the screw, which is employed to move the grating-plate forward by about 1/15,000 of an inch between successive strokes of the diamond, contains almost no errors. It cannot be said, of course,

that the screw is entirely free from error, but the effect of the exceedingly minute irregularities is almost wholly compensated by ingenious devices that form a part of the ruling-engine. The machine is automatic in its action, and when set in motion the ruling of a large grating goes on without interruption for six days and nights before it is completed.

The gratings manufactured on Rowland's machine have gone into observatories and laboratories in all parts of the world, where they have been the principal agents of spectroscopic research during the last quarter of a century. Their great efficiency has caused them to displace prisms from nearly all spectroscopes in which very high resolving power is required. As we shall see later, however, the prism still remains of great importance to the spectroscopist, particularly in work requiring moderate resolving power, where it gives a much brighter spectrum than a grating.

Rowland's contributions to spectroscopy were by no means confined to the manufacture and distribution of optical gratings. In addition to his very extensive researches on the solar spectrum, and on the spectra of the elements, he invented the concave grating, which now forms an essential part of the powerful spectroscopes found in many laboratories. Prior to Rowland's time the comparatively few gratings which had been made were ruled on plane surfaces, and employed with the ordinary collimator and telescope of the laboratory spectroscope. That is to say, the prism of an ordinary spectroscope was removed, and the grating substituted for it. In such an instrument the rays of light, after passing through the slit, fall upon the collimator lens, which renders them parallel. The parallel rays then meet the surface of the grating, where they are diffracted and spread out into a spectrum. This spectrum is observed or photographed with the aid of a second lens, which forms its image on the

retina or on a sensitive plate. A large spectroscope of this kind, used with the 40-inch Yerkes telescope for spectroscopic observations of the Sun, is illustrated in Plate XXX.

Rowland showed, from theoretical considerations, that, if the grating were given a concave spherical surface, the collimator lens, and the observing telescope as well, might be entirely dispensed with. He also devised the form of mounting for a concave grating illustrated in Fig. 3. In the diagram, *a* is the slit through which the light enters, *b* the concave grating, and *c* the eye or photographic plate. It will be seen that no lenses enter into the construction of the apparatus; for some classes of work this is a point of great advantage. In the largest gratings used by Rowland the radius of curvature of the grating-plate, which is equal to the distance between the grating *b* and the photographic plate *c*, is 21 feet. The spectrum given by such a grating is many feet in length, and a portion of the spectrum 20 inches long or longer can be recorded by a single exposure on the photographic plate. In order to pass from one part of the spectrum to another, the grating-carriage *b* is moved along the rail *ab*, which causes the plate-carriage *c* to move toward or away from the slit on the rail *ac*. The whole apparatus is set up on piers in a dark room, to which no light is admitted except that which passes through the slit of the spectroscope.

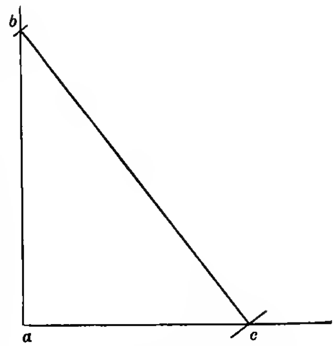


FIG. 3
Diagram of a Concave Grating Mounting

It should be remarked that a grating, unlike a prism, produces not merely a single spectrum, but several spectra, which can be observed successively by moving the carriage *c*

along the track away from the slit. The first-order spectrum lies nearest the slit. The second-order spectrum, twice as long as the first, which it partially overlaps, lies farther from the slit. The third and fourth orders, of increasingly higher dispersion, lie still farther from the slit. Only a portion of the fifth order can be observed with this instrument, and the higher orders, also beyond reach, are usually too faint to be of any service.

Let us suppose that we wish to determine with such a spectroscope whether iron exists in the Sun. To accomplish this, sunlight must be reflected from the mirror of a heliostat (driven by clock-work, to maintain the beam in a fixed direction) to the slit. Between the slit and the heliostat a lens is introduced, for the purpose of forming an image of the Sun upon the slit. When the illumination is secured in this way, the whole grating is filled with light from the diverging rays. The grating then produces an image of the solar spectrum upon the photographic plate, where it may be recorded by giving a suitable exposure.

To facilitate an accurate comparison, the solar spectrum is photographed side by side on the same plate with the spectrum of the substance whose presence in the Sun is to be determined. In order to accomplish this, one-half of the slit is covered, and the sunlight is admitted through the other half. Thus the solar spectrum is photographed on one side of the plate. After this exposure is completed, the sunlight is shut off, and the screen in front of the slit moved so as to cover the half previously open, and to uncover the other half. The image of the Sun on the slit of the spectroscope is then replaced by an image of an electric arc light, burning between two poles of iron. The spectrum of the iron vapor is thus produced on the plate, and a strip of this spectrum is photographed beside the strip of solar spectrum. This is illustrated in Fig. 2, Plate XXII, where the upper

strip is a small part of the spectrum of iron. It will be seen by a glance at this photograph that these bright lines of iron are represented in the solar spectrum by corresponding dark lines, which accurately match them in position. In Rowland's work on the solar spectrum thousands of lines were found to correspond with iron lines given by the electric arc.

The same process can be employed to determine the presence of other substances in the Sun. In the case of metals, the electric discharge may be caused to pass between two metallic rods, or fragments of the metal may be placed in a hole drilled in one of the carbons of an ordinary electric arc-lamp. In the latter case the spectrum of carbon, and also of the impurities which the carbon poles always contain, will appear on the plate with the spectrum of the metal in question. But these extra lines may always be identified, and usually give no trouble. The identification of the solar lines, however, is not always so simple as in the case of iron. Many substances are doubtfully represented in the Sun by only a small number of lines, and it is sometimes very difficult to decide whether a few apparent coincidences are sufficient to warrant one in drawing definite conclusions. The matter is usually determined by ascertaining whether certain well-known groups of lines, which for various reasons are considered to be especially characteristic of an element, are actually represented. If these groups are absent, an apparent coincidence with certain less characteristic lines belonging to the same element should be regarded with suspicion. In the case of gases, the comparison is effected by the aid of vacuum tubes, in which the gas, usually at low pressure, is illuminated by an electric discharge. Thus the lines given by a hydrogen tube in the laboratory have been shown to coincide in position with lines ascribed to hydrogen in the Sun.

After many years of study of the solar spectrum by these

methods, Rowland reached the conclusion that the chemical composition of the Sun closely resembles that of the Earth. Certain elements, such as gold and radium, iodine, sulphur, and phosphorus, chlorine and nitrogen, have not been detected in the Sun. But this does not prove that they are certainly absent, as their level in the solar atmosphere, or the low degree of their absorptive effects might prevent them from being represented. On the other hand, various substances, not yet found on the Earth, are shown by many unidentified lines of the solar spectrum to be present in the Sun. Some, if not all, of these, will probably be discovered by chemists, just as helium was found by Ramsay in cleveite (p. 78). Rowland remarked that if the Earth were heated to a sufficiently high temperature, it would give a spectrum closely resembling that of the Sun.

The most perfect maps of the solar spectrum are those of Rowland and Higgs. These are enlarged from photographs made with the concave grating, and contain an immense number of lines. Both maps extend into the extreme ultra-violet spectrum (the invisible region beyond the violet), and that of Higgs includes a considerable region of the infra-red (also invisible to the eye) where photographic plates sensitized for red light with alizarin blue or other dyes must be employed. Both maps are provided with scales of wave-length, so that the approximate positions of the lines can be read off at once. The precise positions of all solar lines photographed by Rowland are given in his *Preliminary Table of Solar Spectrum Wave-Lengths*, which records the places of about 20,000 lines. This table, although known to contain some small errors, is at present employed by all spectroscopists as the standard of reference. It gives Rowland's identifications of the solar lines, but about two-thirds of the lines have not yet been referred to any known element. Recent investigations of the spectra of various

metals will no doubt permit a considerable number of these lines to be identified.

In any examination of the solar spectrum the observer cannot fail to be struck by the changing appearance of the lines in certain regions. In the yellow part of the spectrum, for example, near the well-known D lines of sodium, the most casual examination will show surprising variations in the intensity of the countless lines which are frequently conspicuous here. How great the change is may be seen in Plate XXV, which is a reproduction of two photographs of this part of the spectrum taken under different conditions. The lines which thus change in intensity are called *telluric* lines, since they are due to the absorption of the gases in the Earth's atmosphere. The region illustrated in Plate XXV contains a large number of lines due to water vapor. Since the amount of water vapor undergoes great variations, it is natural that the intensities of the lines should change accordingly.

All of the telluric lines are most conspicuous in the spectrum of the Sun when it is near the horizon, since in this case the light traverses a very great depth of atmosphere before it reaches the spectroscope. Photographs of the spectrum of the high and low Sun might therefore be expected to show marked differences in the intensity of the telluric lines. This is actually the case, and the method therefore affords one means of identifying lines due to the absorption of our atmosphere. The oxygen in the air produces two similar groups (A and B in Fraunhofer's original designation of the solar lines) which lie at the extreme red end of the solar spectrum. Cornu observed these same groups in the spectrum of an electric light at the summit of the Eiffel Tower, as seen from the École Polytechnique in Paris, at a distance of about 2.7 miles.

An ingenious method was employed by Cornu to distin-

guish the telluric lines from those due to absorption in the Sun's atmosphere. According to Doppler's principle, the lines in the spectrum of the east limb of the Sun must be displaced toward the violet (by motion of approach), and those from the west limb toward the red (recession), since the Sun is rotating on its axis in a period of about twenty-five days. It occurred to Cornu that this fact might give a very delicate means of picking out the telluric lines, since only the lines of solar origin can be displaced by the Sun's rotation, while those due to absorption in the Earth's atmosphere remain in their normal positions. He formed a small image of the Sun on the slit of his spectroscope, by means of a lens which could be made to oscillate rapidly, thus causing the east limb and the west limb of the Sun's image to fall alternately upon the slit. If the spectrum is observed while the image is oscillating, the lines of solar origin will be seen to move rapidly to and fro through a short distance, while the telluric lines will remain fixed. This method was successfully employed by Cornu in an important study of the telluric lines. Other investigations of these lines, which have resulted in the production of extensive maps, have been made by Thollon (continued by Spée), Becker, and McClean. In these investigations the telluric lines were distinguished by observations of the spectrum of the high and low Sun.

If passage of sunlight through our atmosphere is thus competent to produce dark lines in the solar spectrum, it is evident that the sunlight reflected from a planet should show evidence of its double transmission through the planet's atmosphere. This method is actually employed to determine the presence and the composition of the atmospheres of the planets.

Remarkable as was Rowland's success in the manufacture of gratings, and the measurement of wave-lengths with their aid, it has recently been surpassed by Michelson. With the

interferometer, an instrument of his invention, Michelson has established the length of the standard meter of the International Bureau of Weights and Measures, in terms of light-waves. This fixes, with the greatest precision, the wave-length of certain lines in the spectrum of cadmium, and these wave-lengths were adopted at the Oxford meeting (1905) of the International Union for Co-operation in Solar Research as primary standards, on which a new system of wave-lengths, to replace Rowland's system, will be based. Through his invention of the echelon, Michelson has realized a new form of grating, composed of a series of glass plates, precisely equal in thickness, piled one on another like a flight of steps, through which a parallel beam of light is transmitted. The spectra thus produced are of a very high order, and the resolving power surpasses that of Rowland's largest gratings. The echelon spectroscope thus furnishes the means of analyzing compound lines, the members of which lie so close together that they cannot be separated with other instruments.

The latest success achieved by Michelson, however, opens up still greater possibilities in spectroscopy. The echelon can be used only for the study of narrow and sharply defined lines; its application is therefore limited to certain special problems. For more general work, both in the laboratory and in the solar observatory, very large gratings, of high resolving power, are required. Six-inch gratings (ruled on a disk of speculum metal 6 inches in diameter) were successfully made by Rowland. After several years of labor Michelson has completed a ruling-machine with an almost perfect screw, on which he has already made 8-inch and 10-inch gratings. He hopes to produce a 14-inch grating, the largest for which his machine is designed. There is reason to believe that his plan for constructing a ruling-machine with four screws, which should reduce the error to one-fourth its amount in a single screw machine, would result in the

production of good 20-inch gratings. The enormous importance of such gratings, in their application to the study of the Sun, will become clearer as we proceed. One difficulty to be overcome will be recognized when it is remembered that a 20-inch grating, having 12,500 lines to the inch, would contain more than 2,000,000 lines, each about 10 inches long. The microscopic diamond crystal, used to cut all these lines in the hard surface of the speculum metal, must not break, or change its form appreciably, during the entire period of the work.

It is satisfactory to add that Jewell has recently constructed a new ruling machine at the Johns Hopkins University which appears likely, from preliminary tests, to be superior to Rowland's. We thus have good reason to hope that the best existing photographs of the solar spectrum will soon be surpassed.

CHAPTER IX

PHENOMENA OF THE SUN'S SURFACE

THE results described in the last chapter relate to the light of the Sun as a whole, and not to the details of its surface phenomena. In most of the investigations there described similar results might be attained if the Sun were removed to the distance of the nearer stars. In that case it would no longer be possible, even with the most powerful telescope, to detect an appreciable disk, and the solar image would be reduced to a microscopic point, brilliant enough, however, to afford sufficient light for spectroscopic examination. But it has already been pointed out that investigations of the Sun acquire their greatest importance through the comparative proximity of this star to the Earth. All other stars are so far away that no distinction can be drawn between the radiations characteristic of different parts of their disks. The spectroscopist must therefore be content to observe in such cases a composite spectrum, produced by the superposition of the spectra of the various surface phenomena. The Sun, on the other hand, is so near us that its image at the focus of a powerful telescope may have a diameter as great as 7 inches, or even greater.[1] Consequently, the light from any point in this image, corresponding to a small area of the solar surface, can be studied by itself. Our extensive knowledge of the Sun, except that which has been derived from an examination of its light as a whole, is based upon this fact.

The appearance of the Sun in a telescope is illustrated by Plate II, which is a reproduction of a direct photograph.

[1] The actual diameter of the Sun is about 860,000 miles.

The Sun's light is too brilliant to permit of visual observation without some method of reducing its intensity. The best means of accomplishing this is by the aid of the polarizing helioscope, which is attached just in front of the eyepiece of the telescope. The cone of light from the object-glass meets a plane surface in the helioscope, from which it is reflected at an angle such as to polarize the rays. As is well known, the amount of plane polarized light which can be reflected from a second surface depends upon the angle at which the rays meet this surface. Consequently, by rotating the reflecting prism the amount of light which reaches the eye can be varied at will, thus producing an image of any desired brightness. When protected by this device, the eye of the observer of solar phenomena is subjected to even less strain than is frequently experienced in work on fainter objects.

A casual glance at the solar image is sufficient to show that it is much darker near the circumference than at the central part of the disk. This falling-off in brightness toward the limb is probably due to the absorption of a smoke-like envelope, which completely incloses the Sun. The absorption is so marked that near the circumference of the Sun only about 13 per cent. of the violet rays escape. For the blue, green, and yellow rays the percentage of transmitted light increases progressively, until it amounts to about 30 per cent. for the red. It has therefore been concluded that, if this absorbing atmosphere were removed, the color of the Sun would appear blue, since the intensity of the violet rays would be about two and one-half times as great as at present, while the red rays would be only about half again as bright as they are now.

The visible phenomena of the Sun's disk include the sun-spots and the faculae. The general appearance of sun-spots, when seen with a low magnifying power, is shown in Plate II.

Under perfect atmospheric conditions, a large sun-spot, when observed with a powerful telescope, would more closely resemble Plate XXVI, which is reproduced from a drawing made by Langley. The best solar observers agree that this drawing is one of the most perfect representations of spot structure yet obtained. The long narrow filaments, which constitute the penumbra of the spot, reach in toward a dark central region, called the umbra. It must be remembered that the darkness of the umbra is only relative: if observed alone, and not in contrast with the more brilliant surroundings of the photosphere, the great brilliancy of the umbra, surpassing that of the most powerful electric arc-light, would be evident. Knowledge of this fact has been quite sufficient to set at rest the old notion that sun-spots are merely rents in a brilliant cloud-covering of the Sun, through which a dark and cool interior may be seen.

According to Langley's view, the filaments which, taken together, constitute the penumbra are everywhere present on the solar surface. He regarded them as resembling the stalks of a wheat-field, seen on end in the undisturbed photosphere, and revealing more of their true characteristics in the penumbra, where they are bent over and drawn out toward the central part of the spot. Langley believed that we are observing columns of luminous vapors rising from the Sun's interior, the seats of convection currents which bring to the surface the immense supplies of heat radiated by the Sun into space. Separating these luminous columns are darker regions, characterized by a lower degree of radiation.

Such minute details can be recorded only with the greatest difficulty. Under ordinary atmospheric conditions the solar image is not seen as a sharp and well-defined object, but its details are continually blurred by the effect of irregularly heated currents in our atmosphere. Even under the best conditions the moments of very sharp definition are few, and

the greatest patience and perseverance are required on the part of an observer who would record his impressions of the solar structure. At the best, drawings based upon visual observations must be unsatisfactory, since even the skilled hands of Langley could not secure the perfect precision which is so desirable. It accordingly might be hoped that here, as in other departments of solar research, photography would afford the necessary means of securing results unattainable by the eye. Unfortunately, however, this hope has been only partially realized, as a brief consideration of the best results in this field will show.

It is a comparatively simple matter to make a direct photograph of the Sun. It is only necessary to form a solar image, considerably enlarged, upon a "slow" photographic plate, and then to give an excessively short exposure by means of a shutter containing a narrow slit, which is shot across just in front of the plate at very high speed. The light from any part of the Sun reaches the plate only during the brief interval in which the slit is passing the corresponding part of the image. The exposure for any point may thus amount to no more than $\frac{1}{100000}$ of a second. The photograph reproduced in Plate II was taken in this way.

In order to obtain photographs showing the smaller details of the photosphere, it is desirable to use a solar image enlarged to a diameter of from 15 to 30 inches, with photographic plates particularly adapted for this class of work. The best direct photographs hitherto made are those taken by Janssen at the Observatory of Meudon, near Paris. A portion of one of these pictures, representing the great Sun-spot of June 22, 1885, is reproduced in Plate XXVII. The penumbra is not very well shown, since the exposure required for the brighter regions of the surrounding photosphere is too short to bring out its fainter details. Even with sufficient exposure, however, such photographs do not reveal the more

delicate details recorded in Langley's drawings. But they do show, with considerable success, the minute structure of the photosphere, as Plate XXVII illustrates. Here may be seen, autographically recorded, the photospheric "grains" which Langley believed to be the extremities of long filaments reaching down toward the interior of the Sun. Janssen holds a different view, since he regards the bright grains to be small spherical masses of luminous vapor, separated by vacant regions. In chap. xi it will be shown that the results of recent investigations with the spectroheliograph tend to bear out Langley's view.

There can be little doubt that direct photographs of the Sun, showing smaller details than have yet been registered, will ultimately be obtained. Janssen's photographs have all been secured with a small instrument, used in an atmosphere where the conditions are not particularly favorable for work of this character. It is therefore to be hoped that, with much more powerful apparatus, employed in a better atmosphere, the results would be still more satisfactory.

In spite of long study and much discussion, it remains uncertain whether sun-spots are to be regarded as cavities or as elevated regions of the photosphere. At one time it was supposed, mainly as the result of observations made by Wilson, of Glasgow, in the eighteenth century, that sun-spots were saucer-shaped cavities, the penumbra representing the sloping edge of the saucer, with the umbra at the center. More recent investigations, however, have failed to confirm Wilson's observations, though there can be little doubt that the umbra lies below the level of the faculae that usually surround spots. Faculae are elevated regions of the photosphere, and the question remains open whether the level of the umbra is above or below the average level of the photosphere, outside of the faculae.

The only other phenomena visible in direct observations

of the Sun are the faculae. They are usually most numerous in the vicinity of Sun-spots, and near the Sun's limb they are sometimes very conspicuous brilliant objects, covering large areas. Near the center of the Sun, however, they are practically invisible, though faint traces of them can sometimes be made out on photographs taken with a suitable exposure. This increase of brightness toward the Sun's limb is assumed to be due to the elevation of the faculae above the photospheric level, and their escape from a considerable part of that absorption which so materially reduces the brightness of the photosphere. Rising above the denser part of the absorbing veil, and thus suffering but little diminution of light, they appear near the Sun's limb as bright objects on a less luminous background.

Janssen's photographs tend to bear out the assumption that the faculae resemble the rest of the photosphere, differing mainly in their greater altitude. They are shown by these photographs to be resolved into granular elements similar to those that constitute the photosphere. It will be seen later, however, that the faculae play a very important rôle, since they are the regions from which immense masses of vapors rise to the solar surface. These vapors are invisible to the eye, and no trace of them is shown on photographs taken in the manner described above. But they may be photographed with the spectroheliograph, by the method explained in chap. xi.

CHAPTER X

THE SUN'S SURROUNDINGS

THE first observations of the Sun's surroundings date back to an early period. On the occasion of a total eclipse the dark body of the Moon covers the solar disk, cuts off the sunlight which at other times illuminates our atmosphere, and reveals phenomena ordinarily hidden by its glare. It is well known that, if our atmosphere were absent, there would be no such scattering of the sunlight, and the sky would be as dark during the day as it now appears at night. In such a case the stars would be visible by day, as well as the solar corona. Formerly, when no artificial means of reducing this brilliant illumination of the atmosphere were known, all knowledge of celestial phenomena in the immediate vicinity of the Sun was of necessity obtained during total eclipses. The solar corona was thus discovered, and likewise the red flames, or prominences, which do not extend so far from the Sun's surface.

The corona still remains a mysterious phenomenon, since no means has yet been discovered of observing it without an eclipse. Our knowledge is thus confined to the results of observations made during the very brief periods when the Moon shields our atmosphere from illumination by the sunlight. The general appearance of the corona, as seen at the eclipse of May 28, 1900, is illustrated in Plate IV, reproduced from a photograph made by Barnard and Ritchey. It may be described as a faintly luminous veil of light, extending outward in long streamers from the surface of the photosphere to distances of several millions of miles, and exceeded in brilliancy, even in its brightest

parts, by the full Moon. In many ways its streamers resemble those of the aurora borealis, and it is indeed possible that their origin may be ascribed to some similar electrical cause. During the few minutes of a total eclipse they are not seen to undergo change of form, but the outline of the corona does vary greatly from year to year, in sympathy with the general variation of the solar activity described in another chapter. At times of minimum sun-spots the form of the corona resembles that shown in Plate IV. This minimum type is marked by great winglike extensions along the solar equator, and by much shorter streamers, diverging like fans near the Sun's pole. At times of maximum sun-spots the corona is much more extensive in the polar regions, the streamers equaling in length those of the equatorial zone.

Spectroscopic observations have shown that the corona consists mainly of gases unknown to the chemist. That is to say, the lines in its spectrum do not coincide in position with the lines of any terrestrial element. Whether these gases, which are probably very light, will ultimately be found on the Earth cannot be predicted. Like helium, first known in the Sun, they may eventually be encountered, in minute quantities, in some mineral, where they have hitherto escaped the chemist's analysis. The fact that the lower part of the corona gives a continuous spectrum, with a feeble solar spectrum superposed upon it, indicates that minute incandescent particles are present, which are hot enough to radiate white light, and which scatter enough sunlight to account for the presence of the solar spectrum.

It may now be of interest to explain how the solar corona is photographed during a total eclipse of the Sun, especially as the same means are employed during eclipses in photographing the solar prominences, and also because we shall have occasion in a subsequent chapter to refer more at length to the general type of telescope here represented.

It has already been explained that the size of an image of the Sun given by a telescope depends directly upon the focal length of the lens employed. In order to show as distinctly as possible the more minute phenomena of the corona, it is therefore desirable to obtain large-scale photographs of it with a telescope of great focal length. Obviously such an instrument as the 40-inch Yerkes refractor could not easily be transported to the more or less remote regions of the Earth where the passing shadow of the Moon may render a total eclipse visible. Fortunately, however, the size of the focal image does not depend upon the diameter of a lens, but merely upon its focal length. Hence the desired result can be obtained by using a long-focus lens of comparatively small diameter. In some cases such lenses are pointed directly at the Sun, and the motion of the solar image, caused by the Earth's rotation, is compensated for by a corresponding motion of the photographic plate on which the image falls. Another method, which offers various points of advantage, is illustrated in Plate XXVIII, reproduced from a photograph of the horizontal telescope used by the eclipse party of the Yerkes Observatory at Wadesboro, North Carolina, on May 28, 1900.

The essential feature of this instrument is a plane mirror, 12 inches in diameter, which reflects the Sun's rays horizontally through a long tube. The plane of the mirror is parallel to the Earth's axis, and, by means of an accurate driving-clock, the mirror is made to complete a rotation once in 48 hours. Such a motion of the mirror is just sufficient to counteract the effect of the Earth's rotation, and thus to keep the Sun's rays reflected in the same direction for an indefinite period. After leaving the coelostat mirror, the rays fall upon a 6-inch photographic lens, which forms an image upon a sensitive plate at its focus, 61½ feet away. Through the rotation of the mirror the image is maintained at a fixed

position upon the photographic plate, so that any desired exposure may be given.

With this apparatus some remarkably fine photographs of the corona and prominences were obtained by Barnard and Ritchey, of the Yerkes Observatory party (Plate XXIX). During the 87 seconds of the eclipse seven exposures were made, ranging in length from $\frac{1}{2}$ second to 30 seconds. Several of the photographic plates used were 25 × 30 inches in size. To facilitate rapid handling, they were mounted on a wooden carrier 15 feet long, free to move on ball bearings on steel rails extending at right angles to the tube through the entire length of the photographic house. A catch, operated by hand, served to stop the plate-carrier at the proper position for each exposure.

The solar prominences are seen at total eclipses of the Sun, projecting like red flames beyond the dark edge of the Moon (Plate XXIX). With our present knowledge of these phenomena, it seems hardly possible that just prior to the middle of the last century they were regarded by some observers as the illuminated summits of lunar mountains. Their truly solar origin was conclusively demonstrated in 1860, when they were photographed by Secchi and de la Rue, and were shown not to share the motion of the Moon. At that time, however, no conclusions could be drawn as to their chemical composition, and it was not until 1868 that their gaseous nature and their connection with the Sun became known through the use of the spectroscope. It was then found that these immense masses of hydrogen and helium gas rise from a sea of flame (the chromosphere, which completely envelops the Sun), and sometimes attain elevations of hundreds of thousands of miles.

The rarity and brief duration of total eclipses would have limited greatly our knowledge of the prominences, had not Janssen, Lockyer, and Huggins devised an epoch-making

method by which they can be observed on any clear day, in spite of the glare of our atmosphere near the Sun. The instrument which permits this result to be accomplished is the spectroscope, used in conjunction with a telescope. The principle of the method is simple and easily understood. The white light of the sky, when passed through the spectroscope, is drawn out into a long rainbow band, and thereby greatly reduced in intensity. The light of the prominences, on the contrary, is concentrated in the radiations characteristic of hydrogen and helium gas, and the dispersing power of the spectroscope merely separates more and more widely the colored images which correspond to these radiations, without seriously enfeebling them. With the spectroscope they therefore become visible, since their images are brighter than the highly dispersed background of skylight on which they lie.

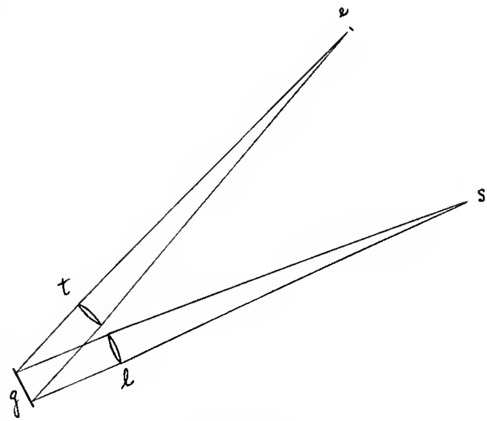


FIG. 4
Diagram of Solar Spectroscope

Plate XXX shows a solar spectroscope suitable for observing the spectra or the forms of the prominences in full sunlight.[1] This spectroscope consists essentially of a slit (*s* in the accompanying diagram, Fig. 4), which may be set tangentially or radially upon the Sun's limb; a collimating lens, *l*, which renders parallel the rays coming to it from the slit; a plane grating, *g*, ruled with about 15,000 lines to

[1] This spectroscope, here shown attached to the Yerkes telescope, was formerly used as a spectroheliograph with the Kenwood telescope (Plate XXXIV).

the inch; and a second lens and eye-piece, *t* and *e*, which form the observing telescope. The grating diffracts the light which reaches it from the collimating lens, and produces a spectrum, an image of which is formed by the lens *t*, in the focal plane of the eye-piece *e*. If it is desired to photograph the spectrum, the eye-piece may be replaced by a sensitive plate.

If we wish, for example, to observe the spectrum of the chromosphere with this instrument, the slit, about 1/1,000 of an inch wide, is made exactly tangential to the solar image. Under these circumstances the observer at the instrument will see the spectrum of the bright sky near the Sun, which is of course merely the spectrum of reflected sunlight, and is therefore crossed by all of the dark Fraunhofer lines. In the case of substances which are present in the chromosphere, the lines of the spectrum will be *reversed* from dark to bright in regions which correspond to the section of the chromosphere lying upon the slit. The most conspicuous bright lines to be observed in this way are the hydrogen lines $H\alpha$ (red), $H\beta$ (blue-green), $H\gamma$ (blue), and $H\delta$ (violet), and the brilliant yellow helium line D_3.

The history of this helium line affords an interesting illustration of the intimacy of the relationship which now unites terrestrial and solar chemistry. In his first observations of the spectrum of the prominences, made in 1868, Lockyer was attracted by the presence of a bright line in the yellow, not far from the position of the D_1 and D_2 lines of sodium. This line was designated as D_3, but all attempts to identify it among the lines of known elements were unsuccessful. Accordingly, it was assumed to represent a new gas, probably very light, on account of its association with hydrogen at great elevations above the solar surface. Lockyer gave the name "helium" to this gas, because of its solar origin. In 1895 Ramsay, while engaged in an analysis of

the mineral cleveite, discovered an unknown gas, which he found to give a yellow line near the position of D_3. The spectroscope he employed was not powerful enough to determine the position of the line with great accuracy, but Runge proved beyond a doubt, a short time later, that the line was actually in the position of D_3. However, he detected a faint companion to this line, on the side toward the red, which had never been observed in the solar prominences. An examination of D_3 in the prominence spectrum, made at the Kenwood Observatory immediately upon the receipt of Runge's description of his laboratory results, showed the undoubted presence of a similar companion, which was found by repeated measures to agree well in position with Runge's determinations. The companion was so faint that it would easily escape observations made without knowledge of its existence. It may be said, however, that this first observation was greatly facilitated by the presence of a very bright prominence, in which D_3 was beautifully shown. Huggins and others detected the duplicity of the line about the same time.

As was anticipated by its behavior in the Sun, helium was found to be the lightest of all known gases, except hydrogen. Further study of the spectrum showed D_3 to be only one of a series of lines, other members of which are also represented in the chromosphere. Many lines characteristic of the spectra of "Orion" stars, which had not been identified before Ramsay's discovery, are also due to helium. It is extremely probable that other new elements, not yet discovered on the Earth, are represented by some of the unknown lines of the solar spectrum.

While the lines of hydrogen and helium are more brilliant and conspicuous than all others in the visible spectrum of the chromosphere, it is nevertheless true that a very large number of lines due to other elements can be seen on any good day with a powerful telescope and spectroscope. The

vapors of magnesium, iron, and several other substances are conspicuously represented by bright lines in the chromospheric spectrum; but these lines are shorter than those of hydrogen and helium, since the vapors do not rise to so great a height. With the Yerkes telescope it is even possible to observe a multitude of fine bright lines due to the vapor of carbon, which lies in close contact with the photosphere. The layer of carbon vapor is so thin that the least motion of the solar image, or a very slight disturbance of the atmosphere, are sufficient to render the lines invisible.

A total eclipse affords a most favorable opportunity to determine photographically the depths of the several layers. The simplest way of accomplishing this is to place a prism over the object-glass of a telescope, which is directed toward the Sun. When, at the moment of totality, the Moon covers the photosphere, arcs of the chromosphere are left projecting beyond the Moon's edge. After passing through the prism, the image formed on the photographic plate will appear like that reproduced in Plate XXXI, which was taken by Lord at the eclipse of 1900. The arcs represented here correspond to the various lines in the spectrum of the chromosphere. In this case, however, since no slit was used in the spectroscope, the form of each arc is defined by the distribution of the corresponding vapor. If a prominence is present at any point, its image will be repeated in each of the arcs representing the element it contains.[1] Of course, this "spectrum of the flash," first observed by Young, and so called on account of its brief duration, can be photographed only during the few seconds while the Moon's edge is passing over the chromosphere.

It will now be seen more clearly how the forms as well as the spectra of the prominences can be observed by the spec-

[1] The prominence group shown in Plate XXIX is faintly represented here (reversed in position) in each of the two stronger arcs.

troscopic method without an eclipse. So long as a narrow slit is employed, the spectrum will consist of narrow lines, having the same form as the slit. That is, if the slit be straight, the lines will be short, straight sections of the chromosphere or prominences, corresponding in width to the slit. If the slit be curved, the lines will have a corresponding curvature. In other words, the lines are simply monochromatic images of the slit. Hence, if the slit be widely opened, the lines will assume the form of that portion of the chromosphere or prominence which happens to lie across it. It is as though one were looking out through a narrow window upon a mass of great flames.

The application of the spectroscopic method to the study of the chromosphere and prominences marked a new era in solar research. Daily observations were inaugurated with great enthusiasm by Lockyer, Young, Janssen, and other astronomers in Europe and America. It was found that the prominences could be divided into two classes—quiescent, or cloudlike, and eruptive. The former are much the more numerous, and may always be seen, in larger or smaller numbers, at the Sun's limb. They change slowly in form, and sometimes persist for days, or until carried out of view by the solar rotation. When seen under excellent atmospheric conditions, the complex details of their structure resemble those of the clouds in our own atmosphere. The eruptive prominences change very rapidly in appearance, sometimes shooting up to elevations of over two hundred thousand miles in a few minutes (see Plates XXXV and XXXVI). Like the quiescent forms, they are most numerous at times of greatest sun-spot activity. They are never observed in very high latitudes, though the quiescent prominences appear at all parts of the solar circumference. The photographic study of these phenomena will be described in the next chapter.

CHAPTER XI

THE SPECTROHELIOGRAPH

THE spectroscopic method, as applied by astrophysicists in various parts of the world, has yielded a nearly continuous record of the solar prominences extending back over more than thirty years. For many purposes such a record is entirely satisfactory, and permits important conclusions to be drawn. But the process of observation is not only slow and painstaking: it is subject to the errors and uncertainties that necessarily attend the hand delineation of any object, seen through a fluctuating atmosphere. Moreover, changes in the forms of eruptive prominences are frequently so rapid that the draughtsman cannot record them. It was principally in the hope of simplifying the process of observation, and of rendering it more rapid and more accurate, that the spectroheliograph was devised at the Kenwood Observatory in 1889.[1]

The principle of this instrument is very simple. Its object is to build up on a photographic plate a picture of the solar flames, by recording side by side images of the bright spectral lines which characterize the luminous gases. In the first place, an image of the Sun is formed by a telescope on the slit of a spectroscope. The light of the Sun, after transmission through the spectroscope, is spread out into a long band of color, crossed by lines representing the various elements. At points where the slit of the spectroscope happens to intersect a gaseous prominence, the bright lines of hydrogen and helium may be seen extending from the base

[1] It was subsequently learned that the method embodied in the spectroheliograph had been suggested by Janssen as early as 1869, reinveuted by Braun of Kalocsa, and actually tried by Lohse at Potsdam. But it had not proved a success.

of the prominence to its outer boundary. If a series of such lines, corresponding to different positions of the slit on the image of the prominence, were registered side by side on a photographic plate, it is obvious that they would give a representation of the form of the prominence itself. To accomplish this result, it is necessary to cause the solar image to move at a uniform rate across the first slit of the spectroscope, and, with the aid of a second slit (which occupies the place of the ordinary eyepiece of the spectroscope), to isolate one of the lines, permitting the light from this line, and from no other portion of the spectrum, to pass through the second slit to a photographic plate. If the plate be moved at the same speed with which the solar image passes across the first slit, an image of the prominence will be recorded upon it. The principle of the instrument thus lies in photographing the prominence through a narrow slit, from which all light is excluded except that which is characteristic of the prominence itself. It is evidently immaterial whether the solar image and photographic plate are moved with respect to the spectroheliograph slits, or the slits with respect to a fixed solar image and plate.

This method, when first tried at the Harvard Observatory in 1890, proved unsuccessful. The lack of success was partly due to the fact that a line of hydrogen was employed. This line, though fairly suitable for the photography of prominences with the perfected spectroheliograph of the present day, was too faint for successful use amidst the difficulties which surrounded the first experiments. Accordingly, when the work was resumed a year later at the Kenwood Observatory in Chicago (Plate XXXIII) an attempt was made, through a photographic investigation of the violet and ultra-violet regions of the prominence spectrum, to discover other lines better fitted for future experiments. In the extreme violet region, in the midst of two

broad dark bands which form the most striking feature of the solar spectrum, two bright lines (H and K) were found and attributed to the vapor of calcium. They had previously been seen visually by Young, but, on account of the insensitiveness of the eye for light of this color, they could not be observed satisfactorily. A careful study soon showed them to be present in every prominence examined, at elevations above the solar surface equaling or exceeding those attained by hydrogen itself (Plate XXXII, *a*). Their suitability for the purpose of prominence photography is due to several causes, among which may be mentioned their exceptional brilliancy, their presence at the center of broad dark bands which greatly diminish the brightness of the sky spectrum, and the comparatively high sensitiveness of photographic plates for light of this wave-length.

While fairly efficient from an optical point of view, the spectroheliograph of the preceding year had possessed many mechanical defects. It sufficed to give photographs of individual prominences, but they were not very satisfactory. In a new instrument, devised for use with the 12-inch Kenwood telescope, the principal defects were overcome, and means of securing the necessary conditions of the experiment were provided. The Kenwood spectroheliograph is shown in Plate XXXIV. In this instrument the solar image and photographic plate were fixed, while the first and second slits were made to move across them by means of a system of levers, set in motion by hydraulic power. The first trials of the instrument, made in January, 1892, were entirely successful, and the chromosphere and prominences surrounding the Sun's disk were easily and rapidly recorded (Plates III, XXXV, and XXXVI). The details of their structure were shown with the sharpness and precision characteristic of the best eclipse photographs. And the opportunity for making such records, previously limited to the brief dura-

tion, never exceeding seven minutes, of a total eclipse, was at once indefinitely extended. Thus it became possible to study photographically the slowly varying forms of the quiescent, cloudlike prominences, and, to particular advantage, the rapid changes of violent eruptions.

But even before this primary purpose of the work had been accomplished, the possibility of making another and much more important application of the instrument had presented itself. A photographic study of the spectrum of various portions of the Sun's surface had shown the existence at many points of great clouds of calcium vapor, luminous enough to render their existence evident through the production of bright H and K lines on the solar disk (Plate XXXII, *b* and *c*). Some of these calcium clouds had, indeed, been known to exist through the important visual observations of Young, who had observed the bright H and K lines in the vicinity of sun-spots. But the vast extent and the characteristic forms of the phenomena could not be ascertained by such means. What was required was such a representation of the solar disk as the spectroheliograph had been designed to give in the case of the prominences. From a consideration of the results obtained in the spectroscopic study of the disk, it appeared probable that an important application of the spectroheliograph might be made in this new direction.

Before describing this second application of the instrument, it may be well to recall the appearance of the Sun when seen with a telescope, or when photographed in the ordinary manner without a spectroheliograph. From photographs like that reproduced in Plate II, we see that the most conspicuous features of the solar surface, at least so far as the eye can detect, are the well-known sun-spots. The bright faculae, which rise above the photosphere, are conspicuous when near the edge of the Sun, but practically

invisible when they happen to lie near the center of the disk. The bright H and K lines, referred to in the last paragraph, were found in close association with the faculae, and it appeared probable that much of the highly heated calcium vapor, to which these bright lines are due, rises from the interior of the Sun through the faculae. It was therefore to be expected that a successful application of the spectroheliograph to the photography of the luminous calcium clouds would give bright forms resembling those of the faculae. Furthermore, it was to be hoped that these brilliant clouds could be recorded, not only near the limb of the Sun, but also in the central part of the disk, since the bright reversals of the H and K lines were equally well photographed in all parts of the image.

The results of the first experiments, which were made at the beginning of 1892, were such as to justify fully the expectations that had been entertained. It was at once found possible to record the forms, not only of the brilliant clouds of calcium vapor associated with the faculae, and occurring in the vicinity of sun-spots, but also of a reticulated structure extending over the entire surface of the Sun. The earliest use of the method was made in the study of the great sun-spot of February, 1892, which, through the great scale of the phenomena it exhibited and the rapid changes that resulted from its exceptional activity, afforded the very conditions required to bring out the peculiar advantages of the spectroheliograph. In the systematic use of the instrument continued at the Kenwood Observatory through the following years, a great variety of solar phenomena were recorded, and the changes which they underwent from day to day—sometimes, in the more violent eruptions, from minute to minute—were registered in permanent form. During this period, which ended with the transfer of the Kenwood instruments to the Yerkes Observatory, over 3,000

photographs of solar phenomena were secured. From a systematic study of these negatives, in the course of which the heliographic latitude and longitude of the calcium clouds (subsequently named the *flocculi*) in many parts of the Sun's disk were measured from day to day (by Fox), a new determination of the rate of the solar rotation in various latitudes has been made. This shows that the calcium flocculi, like the sun-spots, complete a rotation in much shorter time at the solar equator than at points nearer the poles. In other words, the Sun does not rotate as a solid body would do, but rather like a ball of vapor, subject to laws which are not yet understood.

In this first period of its career the spectroheliograph had therefore permitted the accomplishment of two principal objects. It had provided a simple and accurate means of photographing the solar prominences in full sunlight, which gave results hardly inferior to those obtained during the brief moments of a total eclipse. It had also given a means of recording a new class of phenomena, known previously to exist only through glimpses of the bright calcium lines in the vicinity of sun-spots, but wholly invisible to observation, either visually or on photographs taken by ordinary methods. It was not difficult to see, however, that the possibilities of the new method were much greater than had been indicated by the work so far accomplished. It seemed probable that our knowledge of the finer details of the calcium flocculi would be greatly increased if provision could be made for photographing a much larger solar image with a spectroheliograph of improved design. And it was furthermore evident that other applications of the instrument, involving the use of different spectral lines, and the employment of principles which had not been thoroughly tested in the earlier work, might reasonably be hoped for. Attempts were, indeed, made to photograph the Sun's disk with the

dark lines of hydrogen, but the Kenwood spectroheliograph was not well adapted for this purpose.

The 40-inch telescope of the Yerkes Observatory provided the first requisite for the new work—namely, a large solar image, having a diameter of 7 inches as compared with the 2-inch image given by the Kenwood telescope. The construction of a spectroheliograph large enough to photograph such an image of the Sun involved serious difficulties, but these were finally overcome. The Rumford spectroheliograph, designed to meet the special conditions of the new work, was built in the instrument shop of the Yerkes Observatory, and is now in daily use with the 40-inch telescope (Plate XXXVII).

In this instrument the solar image is caused to move across the first slit by means of an electric motor, which gives the entire telescope a slow and uniform motion in declination. The sunlight, after passing through the first slit, is rendered parallel by a large lens at the lower end of the collimator tube. The parallel rays from this lens fall upon a silvered glass mirror, from which they are reflected to the first of two prisms, by which they are dispersed into a spectrum (Plate XLI, Fig. 1). After passing through the prisms, the light, which has now been deflected through an angle of 180°, falls upon a second large lens at the lower end of the camera tube. This forms an image of the spectrum at the upper end of the tube, where the second slit is placed. Any line in the spectrum may be made to fall upon this slit, by properly adjusting the mirror and prisms. Above the slit, and nearly in contact with it, the photographic plate is mounted in a carriage, which runs on rails at right angles to the length of the slit. The rails are covered by a light-tight camera box, so that no light can reach the plate except that which passes through the second slit. While the solar image is moving across the first slit,

the plate is moved at the same rate across the second slit, by a shaft leading down the tube from the electric motor, and connected, by means of belting, with screws that drive the plate-carriage.

Photographs of the solar disk taken with this instrument under good atmospheric conditions reveal a multiplicity of fine details (Plate XXXVIII). The entire surface of the Sun is shown by these plates to be covered by minute luminous clouds of calcium vapor, only about a second of arc in diameter, separated by darker spaces, and closely resembling in appearance the well-known granulation of the solar photosphere (Plate XXXIX). A sharp distinction must, however, be drawn between this appearance, which is wholly invisible to the eye at the telescope, and the granulation of the photosphere. In accordance with Langley's view, the grains into which the solar surface is resolved under good conditions of visual observation are the extremities of columns of vapor rising from the Sun's interior. They seem to mark the regions at which convection currents, proceeding from within the Sun, bring up highly heated vapors to a height where the temperature becomes low enough to permit them to condense. It might be anticipated that out of the summits of these condensed columns, other vapors, less easily condensed, would continue to rise, and that the granulated appearance obtained with the spectroheliograph may represent the calcium clouds thus ascending from the columns (Plate XL). We might, indeed, go a step farther, and imagine the larger and higher calcium clouds to be constituted of similar vaporous columns, passing upward through the chromosphere, and perhaps at times extending out into the prominences themselves. A means of research now to be described, which represents another application of the spectroheliograph, involving a new principle, seems competent to throw some light on this question.

Mention has already been made of the faculae, which are simply regions in the photosphere that rise above the ordinary level. Near the edge of the Sun their summits lie above the lower and denser part of that absorbing atmosphere which so greatly reduces the Sun's light near the limb, and in this region the faculae may be seen visually. At times they may be traced to considerable distances from the limb, but as a rule they are inconspicuous or wholly invisible toward the central part of the solar disk. The Kenwood experiments had shown that the calcium vapor coincides closely in form and position with the faculae, and hence the calcium clouds were long spoken of under this name. In the new work at the Yerkes Observatory the differences between the calcium clouds and the underlying faculae became so marked that a distinctive name for the vaporous clouds appeared necessary. They were therefore designated *flocculi*, a name chosen without reference to their particular nature, but suggested by the flocculent appearance of the photographs.

In order to analyze these flocculi and to determine their true structure, a method was desired which would permit sections of them at different heights above the photosphere to be photographed. Fortunately there is a simple means (first described by Deslandres) which appears to accomplish this apparently difficult object. At the base of the flocculi the calcium vapor, just rising from the Sun's interior, is comparatively dense. As it passes upward through the flocculi it reaches a region of much lower pressure, and during the ascent it might be expected to expand, and therefore to become less dense. Now we know from experiments in the laboratory that dense calcium vapor produces very broad spectral bands, and that, as the density of the vapor is decreased, these bands narrow down into fine, sharp lines (Plate XLI, Fig. 2). An examination of the solar spectrum

will show that the H and K lines of calcium give evidence of the occurrence of this substance under widely different densities in the Sun. The broad dark bands, which for convenience we designate H_1 and K_1, are due to the low-lying, dense calcium vapor (Plate XXXII). At their middle points (over flocculi) are seen two bright lines, which are much narrower and better defined. These lines, designated H_2 and K_2, are the ones ordinarily employed in photographing the flocculi with the spectroheliograph. Superposed upon these bright lines are still narrower dark lines, due to the absorption of cooler calcium vapor at higher elevations (H_3, K_3). It will be seen that the evidence of the existence of calcium vapor at various densities in the Sun is apparently complete, and that we may here find a way of photographing the vapor at low levels without admitting to the photographic plate any light that comes from the rarer vapors at higher levels. It is simply necessary to set the second slit of the spectroheliograph near the edge of the broad H_1 or K_1 bands, in order to obtain a picture showing only that vapor which is dense enough to produce a band of width sufficient to reach this position of the slit. No light from the rarer vapors above can enter the second slit under these circumstances, since they are incapable of producing a band of the necessary width.[1]

The great sun-spot of October, 1903, afforded an opportunity to try this method in a very satisfactory manner. Sections of the calcium vapor in the neighborhood of this spot-group, corresponding to the two different levels photographed on October 9, are shown in Figs. 1 and 2, Plate

[1] The bright regions photographed in this way resemble the faculae very closely, and may be regarded as essentially identical with them, since the white light from the continuous spectrum of the faculae contributes in an important degree to the formation of the photographic images. However, any dense calcium vapor which extends beyond the boundaries of the faculae will be recorded on the photograph. In any case we should expect the dense calcium vapor, supposed to be rising from the faculae, to correspond closely with them in form.

XLII.[1] The manner in which the vapor at the H_2 level overhangs the edge of the sun-spot is very striking, and thorough study should throw some light on the conditions which exist in such regions. For it is possible, not only to photograph sections of the vapor at various levels, but also to ascertain, by the displacement of the H_2 or H_3 line, as photographed by a powerful spectrograph, the direction and velocity of motion of the vapor which constitutes the flocculi. It is commonly found that the vapor is moving upward at the rate of about one kilometer per second, though the velocity varies considerably at different points and under different conditions.

The photographs occasionally show the existence of flocculi remarkable for their great brilliancy. In these regions active eruptions are in progress. The vapor, rendered highly luminous by intense heat or other causes, is shot out from the Sun's interior with great velocity. Consequently there are rapid changes in the forms of these brilliant regions, whereas the ordinary flocculi change slowly, and represent a much less highly disturbed condition of affairs. The brilliant eruptive flocculi always occur in active regions of the solar surface, and probably correspond with the eruptive prominences sometimes photographed projecting from the Sun's limb. A remarkable instance was recorded on the Kenwood photographs, which showed four successive stages of an eruption of calcium vapor on an enormous scale. A vast cloud thrown out from the Sun's interior completely blotted from view a large sun-spot, and spread out in a few minutes so as to cover an area of four hundred millions of square miles.

[1] Although these photographs have been arranged for comparison with the stereoscope, it is to be understood that no stereoscopic effect in the ordinary sense will be obtained in examining them. The purpose of using the stereoscope is simply to allow the images to be superposed, thus permitting them to be seen at the same point in rapid succession by moving a card so as to cover alternately the two lenses of the stereoscope. Thus the manner in which the calcium flocculi overhang the penumbra, and sometimes the umbra, of spots can be observed.

Although the eruptive flocculi probably correspond in many instances with eruptive prominences, it must not be concluded that the quiescent calcium flocculi correspond with the quiescent, cloudlike prominences. As a matter of fact, we have good evidence for the belief that the flocculi shown in these photographs represent in most instances comparatively low-lying vapors, while the prominences, which extend above the level of the chromosphere, do not ordinarily reveal themselves as bright objects in projection against the disk.

So far, we have considered the photography of the Sun with the light of the H and K lines of calcium. But it must naturally occur to anyone familiar with the solar spectrum that it should be possible to take photographs corresponding to other lines, and thus representing the vapors of other substances. For the darkness of the lines is only relative; if they could be seen apart from the bright background of continuous spectrum on which they lie, these lines would shine with great brilliancy. It is thus evident that, if all light except that which comes from one of these dark lines can be excluded from the photographic plate by means of the second slit of the spectroheliograph, it should be possible to obtain a photograph showing the distribution of the vapors corresponding to the line in question.

At this point attention should be called to the extreme sensitiveness of the spectroheliograph in recording minute variations in the intensity of a line—variations so slight that no trace of them can be seen in a spectrum photograph showing only the line itself. A well-known physiological effect is here concerned, for it is common experience that the eye cannot detect minute differences of intensity in various parts of an extremely narrow line, whereas these would become conspicuous if the line were widened out into a band of considerable width. The spectroheliograph

records side by side upon the photographic plate a great number of images of a line which, taken together, build up the form of the region from which the light proceeds. In this way the full benefit of the physiological principle is derived, and very minute differences of intensity at various parts of the solar disk are clearly registered upon the plate.

It is obviously essential in photographing with the dark lines to exclude completely the light from the continuous spectrum on either side of the line employed. The admission of even a small quantity of this light might completely nullify the slight differences of intensity recorded by the aid of the comparatively faint light of the dark line. As the second slit cannot be narrowed beyond a certain point, it is evident that for successful photography with the dark lines their width must be increased by dispersion in the spectroheliograph to such a degree as to make them wider than the second slit.

The first satisfactory photographs obtained with dark lines were made with the Rumford spectroheliograph in May, 1903. The lines of hydrogen were chosen for this purpose, on account of their considerable breadth, and because of the prominent part played by this gas in the chromosphere and prominences. In order to secure sufficient width of the lines, the mirror of the spectroheliograph was replaced by a large plane grating having 20,000 lines to the inch. After leaving the grating the diffracted light enters the prisms, where it is still further dispersed before the image of the spectrum is formed upon the second slit. The effect of the prisms is not only to give additional dispersion, but also to reduce the intensity of the diffuse light from the grating—a most important matter in work of this nature. The hydrogen lines employed were $H\beta$, $H\gamma$, or $H\delta$, in the green-blue, blue, and violet, respectively.

On developing the first plate it was surprising to find evidences of a mottled structure covering the Sun's disk, resembling in a general way the structure of the calcium flocculi, but differing in the important fact that, whereas the calcium flocculi are bright, those of hydrogen are dark (Plate XLIII). This result was confirmed by subsequent photographs, and it was found that in general the hydrogen flocculi are dark, although in certain disturbed regions bright hydrogen flocculi appear. Some of these are eruptive in character, and correspond closely with the brilliant eruptive calcium flocculi. But in other cases, in regions where no violent eruptive disturbances seem to be present, the hydrogen flocculi frequently appear bright instead of dark (Plate LXXII). Such regions are usually in the immediate vicinity of active sun-spots, where it is probable that the temperature of the hydrogen is considerably higher than in the surrounding regions. Since a higher temperature would undoubtedly produce increased brightness, the spectroheliograph thus seems to afford a method of distinguishing between regions of higher and lower temperature—an additional property which should prove of great value in investigations on the vapors associated with sun-spots. It is possible, of course, that the increased brightness is due, not merely to an increase of temperature, but to other causes, perhaps of a chemical or electrical nature, which are not yet understood. But the assumption that increased temperature is the effective cause may be provisionally accepted as very probable.

The comparative darkness of the ordinary hydrogen flocculi evidently indicates that this gas in the flocculi for some reason radiates less light than the hydrogen gas which, probably after diffusing from the flocculi, has spread in a nearly uniform mass over the entire surface of the Sun. The simplest hypothesis is to assume that the diminished brightness of the flocculi is due to the reduced temperature in the upper

chromosphere, where the absorption probably occurs. The results of work at Mount Wilson, described in chap. xvi, seem to render this view probable. It should be emphasized at this point, however, that the explanation of spectroheliograph results offered in this chapter is merely an hypothesis, which subsequent investigation may not prove to be correct. According to Julius, the flocculi are not luminous clouds, but the effects of anomalous dispersion of light passing out from the Sun's interior through vapors of unequal density (see p. 148).

The Rumford spectroheliograph was also used to secure photographs with some of the stronger dark lines of iron and other substances. But even with the grating the dispersion was insufficient to give thoroughly trustworthy results, except in a very few cases. It was evident that much greater dispersion must be employed in order to realize the full advantages of the method in future work. Subsequent progress in the development of the spectroheliograph is described in chap. xvi.

Within a short time after the first work at the Kenwood Observatory the spectroheliograph came into general use. Evershed constructed and successfully used one of these instruments in England, and a year later Deslandres, whose admirable work on the spectra of the flocculi was contemporaneous with the investigations at the Kenwood Observatory, undertook systematic research with a spectroheliograph at the Paris Observatory. His contributions to the development of the instrument have been very valuable. Other spectroheliographs are now used daily in India, Sicily, Spain, Germany, England, and the United States.

CHAPTER XII

THE YERKES OBSERVATORY

THE formulation of the theory of natural selection by Darwin was the result of an extensive series of closely correlated investigations, covering a broad field. His object was not merely to bring together a great collection of plants or animals, describe their peculiarities, and confer upon them appropriate names. To Darwin each of these plants and animals might be of great interest. But brilliant plumage, unusual form, and other distinctive peculiarities were of importance to him mainly because of their bearing upon the question of development, or the possible relationship of the particular specimen to others. It is obvious that a study of such relationships must greatly enhance, rather than diminish, the interest of the investigator in the peculiarities which distinguish species. Having in mind a governing principle, he may detect, through the aid of delicate markings or minute modifications of form which might otherwise be inappreciable, the evidences of development which constitute the prime object of his search.

Similar tendencies toward unification and correlation have shown themselves in every department of science. Co-operative undertakings on a large scale, which have enlisted the best efforts of scientific men in all parts of the world, are common at the present time. It may confidently be predicted that the future will see such work greatly extended, and that the various agencies which can thus be employed to advance science will be utilized in an increasingly effective manner.

In astronomical and astrophysical research the opportu-

nities for co-operation and correlation are unusually good, and have yielded many important results. The impossibility of completing at any one observatory the extensive investigations required for the solution of large cosmical problems, and the advantages which may result from the discussion of observations made simultaneously or at stated intervals from stations differing widely in geographic position, altitude, or climatic conditions, render co-operation essential in many cases. Plans for international co-operation in solar research are mentioned elsewhere. An attempt to provide for the closest possible correlation of work within a single observatory is also described in this book.

In establishing an observatory, either one of two policies, both represented in existing institutions, may be adopted. On the one hand, attention may be directed to the prosecution of individual researches or extensive routine investigations, not necessarily closely related to one another, but each constituting an important contribution to knowledge. On the other hand, a single large problem may be chosen, and all individual investigations planned so as to lead as directly as possible toward its solution. The observations required may be very diverse, and cover a broad field. Each, however, to be most effective for its purpose, must be chosen with special reference to the existing needs, and the general programme must be revised from time to time, in the light of every important advance.

The Yerkes Observatory may serve as an example of an institution in which extensive individual investigations, differing widely in character, comprise the programme of research.[1] Its scheme of work was based on a deliberate intention to realize the fullest possible advantages of the 40-inch refractor in the diverse researches for which it is

[1] In the astrophysical work, however, an effort was made to correlate the solar, stellar, and laboratory investigations.

peculiarly adapted. The object of the Mount Wilson Solar Observatory of the Carnegie Institution, however, is to concentrate its entire attention upon the study of the Sun and the problem of stellar evolution.

After the spectroheliograph had been tested at the Kenwood Observatory, it seemed certain that this method was capable of further extension, and the desirability of securing better instrumental facilities accordingly presented itself. The establishment of the new University of Chicago appeared to offer the best prospects in this direction. The opportunity of purchasing two disks of glass for the objective of a 40-inch refractor was encountered in 1893. This glass had been ordered three years before for a telescope to be erected on Mount Wilson in southern California—an odd coincidence in the light of subsequent events. As funds were not available for the completion of the California project the glass disks, then in the hands of Alvan Clark & Sons, were obtainable. The opportunity was an unusual one, since the disks were of the largest size and of the most perfect optical glass. After several unsuccessful attempts to secure the funds from other sources, the matter was placed before Mr. Charles T. Yerkes by President Harper. He promptly signified his desire to provide for the construction of a 40-inch refractor. The glass was purchased, a contract arranged with Clark to complete the object-glass, and the mounting ordered from Warner & Swasey. The construction of the Yerkes Observatory was undertaken in 1895 and completed in 1897.

The gift which provided for the Yerkes Observatory was made before the University of Chicago had opened its doors to students. In fact, the original idea of establishing a college, rather than a university, had hardly been outgrown, and the question of the recognition to be accorded to research was still a cause of concern to the members of the rapidly

enlarging faculty. A narrow view of the future on the part of the trustees might have led to the erection of the observatory in Chicago, and its use for the purposes of instruction rather than for those of research. Fortunately, a different policy prevailed. It was recognized that the 40-inch telescope should be exclusively devoted to investigation, and that a site in the immediate neighborhood of the university grounds would prevent its effective use. It was accordingly decided to secure a site in the most favorable location within a reasonable distance of Chicago, and a tract of land in Wisconsin, on the shore of Lake Geneva, was finally selected.

The plan of the building shows the influence of the Lick Observatory and the Astrophysical Observatory of Potsdam, both of which embody many admirable features. The adopted form of a Roman cross permitted the three domes to be separated to such an extent that they practically do not interfere in the least with one another (Plate XLIV). The desire of the donor for an ornate structure, and the decision of the architect to introduce rather florid embellishments of terracotta, led to the use of brick as a building material. This was quite in accordance with convention, but in conflict with the condition, well known to astronomers, that the temperature within an observing-room should be as nearly as possible the same as the temperature of the outer air. The massive brick wall of the great tower in which the 40-inch telescope is mounted is therefore decidedly inferior to a light steel construction, with a thin metallic wall, shielded from the Sun by an outer wall of similar type. Architectural considerations, however, have weighed as heavily in nearly all of the world's largest observatories, and the complete freedom of action, subsequently experienced at Mount Wilson, had not yet been attained.

The engineering problems presented by the great size

of the Yerkes telescope, and of the dome under which it was mounted, were such as to tax the efforts of even so skilful a firm as that of Warner & Swasey, to whom the work was intrusted. The admirable qualities of the mounting of the Yerkes telescope show the advantage of the experience gained by them in constructing the Lick telescope. The dome and rising-floor, after several faults of design and construction had been remedied, also performed very well. Thoroughly tested by continuous use, by night and by day, for a period of ten years, the entire plant may certainly be considered to reflect much credit upon these well-known engineers.

The 40-inch telescope, and other instruments of the Yerkes Observatory, have already been described in previous chapters, but a few additional details may be of interest. The object-glass, which was put in place only a few weeks before the death of Alvan G. Clark, the last member of the celebrated firm of Alvan Clark & Sons, is made up of two lenses. The outer lens, made of crown glass, is double convex in form (Plate XLV). The inner lens, separated from the other by a distance of about eight inches, is plano-concave, and made of flint glass. The total weight of the glass in the two lenses is about 500 pounds. The rough glass disks, from which the lenses were fashioned by the Clarks, were made by Mantois, of Paris. The glass is of extraordinary purity and transparency, but in spite of this fact it absorbs much light, on account of its considerable thickness (about three inches in all). The conditions are very different from those of a reflecting telescope, where much less perfect glass is required, since in the latter case the light is reflected from a layer of pure silver on the front surface and therefore suffers no absorption in transmission (though some light is lost in reflection). It has already been pointed out that refracting and reflecting telescopes have their own peculiar advantages and defects. The choice of the one or

the other must depend upon the needs of the work for which it is required.

In order to direct the 40-inch telescope to a faint star, the sidereal time, as well as the right ascension and declination of the star, must be known. After the opening in the dome has been turned toward the proper quarter of the heavens, the telescope is moved in right ascension (i. e., around the polar axis, which is parallel to the Earth's axis) until the hour circle, attached to this axis, indicates the proper reading. This reading is determined by taking the difference between the sidereal time and the right ascension of the star. The result gives the distance of the star from the meridian, expressed in hours and minutes of time. The motion of the telescope in right ascension is produced by means of an electric motor, controlled by a rope running down the north face of the iron column and easily reached from the rising-floor. The next operation is to move the telescope in declination (i. e., around an axis at right angles to the polar axis) until the declination circle indicates the proper reading, so many degrees north or south of the equator. If the eye-end of the telescope is then too high to be reached by the observer on the rising-floor, the floor is raised by means of an electric motor, controlled by a switch near the telescope column. An adjoining switch controls the motor which turns the dome. On looking into the eye-piece the star will be found in the field, provided the setting has been accurately made. The telescope is next clamped in right ascension and declination. It will then be carried by the driving-clock, which causes the polar axis to rotate through a complete revolution in twenty-four hours. The apparent motion of the star in the heavens is thus counteracted, and the image remains fixed in the field of view, where it may be studied in any way desired.

If, for example, the observer wishes to measure the posi-

tion of the star with respect to other stars in its neighborhood, this is accomplished by means of a position micrometer, in which a fine spider line can be moved through the necessary distance by a micrometer screw. The value of one division of the micrometer head, in seconds of arc, is previously determined by measuring the distance between two known stars, whose positions have been accurately fixed by means of a meridian circle. Burnham's admirable observations of double stars with the 40-inch telescope have all involved the accurate micrometric measurement of the distance separating the stars of each pair. The position angle of the line joining the two stars, with reference to a north-and-south line in the heavens, is also measured in each case with the aid of a divided circle attached to the micrometer. On account of the large aperture of the telescope, it is possible to separate with it stars about one-tenth of a second of arc apart, provided the atmospheric conditions are sufficiently good for the purpose. As the distance between the two images in the principal focus of the telescope would, in this case, amount to but little over one three-thousandth part of an inch, it is obvious that the best of conditions are required for such exacting work.

Barnard's observations with the Yerkes telescope have also involved the constant use of the micrometer. The difficulty of the work, and the patience required to pursue it, can be imagined when it is remembered that Barnard has measured the positions of hundreds of stars in such a closely crowded cluster as that illustrated in Plate XIX. In such work as this the observer remains standing throughout the entire night. It should also be remembered that in the open dome the temperature sometimes falls to $-20°$ F. in the rigorous Wisconsin winters. It is evident that only the greatest interest and devotion on the part of the observer can permit him to make accurate measures, night after night, under such conditions.

We have already seen (in chap. xi) how the Rumford spectroheliograph is used with the Yerkes telescope. As the spectroheliograph weighs about 700 pounds, and must be attached each morning and taken off at night, special arrangements are required to facilitate this work. Each heavy instrument used in conjunction with the telescope is mounted on a carriage, which stands on the rising-floor. When the change is to be made from one attachment to another, the floor is raised to its highest position and the telescope tube firmly anchored to it by means of a steel bar. This is to obviate any danger of accident when the balance of the tube is temporarily disturbed. The carriage bearing the spectroheliograph is brought to the eye-end of the telescope, the spectroheliograph clamped to its supporting ring, and over 700 pounds of iron weights removed from the telescope tube. This restores the balance, which must be adjusted to a nicety.

The Bruce spectrograph (Plates XLVI and LXXVIII) is used by Frost for the photographic study of stellar spectra. The image of a star is formed on the slit of the spectrograph, which is about one-thousandth of an inch in width. The light then passes to a collimator lens, which renders the rays parallel. Three large prisms, next traversed by the rays, bend them through an angle of 180° and disperse them into a spectrum. The camera lens forms an image of the spectrum upon the photographic plate. Throughout the exposure, which may be continued several hours, the observer watches the star image and keeps it accurately on the slit, any imperfections in the driving of the telescope being corrected by means of electric slow motions. In order to eliminate the effect of the changing temperature in the open dome, the spectrograph is inclosed in a tight-fitting case, the interior of which is maintained at a uniform temperature by electric-heating coils.

In order to determine the position of the lines in a spectrum, a suitable comparison spectrum is required. This is obtained by passing an electric spark between poles of titanium or iron and photographing the spectrum of the spark on each side of that of the star. An enlargement of one of Frost and Adams' photographs of η *Leonis*, made in this way, is reproduced in Plate XLVII. It will be seen that the lines of the comparison spectrum are shifted a slight distance toward the red (right), with reference to the corresponding lines in the star. This shift is due to the motion of the star away from the Earth, which in this instance amounts to 28 kilometers per second. On account of its orbital motion, the Earth was moving toward the star on this date at the rate of 26 kilometers per second. Hence the velocity of η *Leonis* with respect to the Sun was $+2$ kilometers per second.

Such displacements of the lines provide the only means of determining whether a star is approaching or receding from the Earth. This method, first tried visually by Huggins, was successfully adopted for photographic work by Vogel, and subsequently greatly refined by Campbell, who applied it with remarkable success at the Lick Observatory. In the hands of Campbell, Frost, and others, it has resulted in the discovery of many "spectroscopic binaries"—double stars in which the component members are revolving at such great velocities that they periodically displace the lines in their spectra. In most of these binaries one of the components is a dark star. Our only clue to their duplicity is thus furnished by the fact that the lines move back and forth with respect to the comparison lines, the displacement being toward the violet when the star is approaching, and toward the red when it is receding from the Earth. In a subsequent chapter it will appear how photographs of stellar spectra are used in the study of stellar evolution.

The Rumford spectroheliograph and the Bruce spectrograph were constructed in the instrument shop of the Yerkes Observatory. It had long been customary for observatories to provide means of repairing their own instruments, but the work of construction had, as a rule, been left to the professional instrument-makers. At the Yerkes Observatory a well-equipped shop was not only a convenience, but a necessity. The funds given for the establishment of the observatory did not provide for a general equipment of minor instruments. In the absence of the means of purchasing instruments, the only alternative was to construct them. Fortunately, a number of machine tools had formed part of the equipment of the Kenwood Observatory and were immediately available. The appropriations of the University of Chicago permitted a skilled instrument-maker to be regularly employed, and special gifts, received from various sources in subsequent years, sometimes enabled us to keep several men at work. The instrument shop, at first under the direction of Wadsworth and subsequently under Ritchey (who was in charge of the optical shop from the beginning), proved to be indispensable to the success of the Observatory's work. Not only the instruments already mentioned, but also the 2-foot reflector, the Snow telescope, a $3\frac{1}{4}$-inch transit instrument, spectroscopic and other apparatus used in the laboratory, and many special instruments and appliances employed with the 40-inch telescope and in other departments of the work, came from this source. It may be said that in a large astrophysical observatory, where new types of instruments are constantly being devised, a well-equipped instrument shop is essential if the best results are to be obtained. This is largely because of the advantage of having the instruments constructed under the immediate supervision of the men who are responsible for their design.

The optical shop was another feature of the Yerkes

Observatory which contributed in a most important manner to its work. Here Ritchey made numerous mirrors—plane, concave, and convex—for use in the Snow telescope, the 2-foot reflector, and other instruments, and here also he did a large part of the work on the 60-inch mirror, which was subsequently transferred to the Solar Observatory. As the methods employed in grinding and polishing this mirror are described in chap. xxiii, no further mention will be made of them here. It may be said, however, that many special investigations set on foot at the Yerkes Observatory could not have been undertaken without the unique advantages afforded by the optical shop.

Still another feature of the Yerkes Observatory, which was subsequently repeated, in improved form, at Mount Wilson, is the spectroscopic laboratory, in which various solar and stellar phenomena are imitated experimentally. Apparatus for producing sparks between metallic poles in air, in liquids, and in compressed gases is arranged on the circumference of a circular table. Low-voltage arcs are also provided, the purpose of the equipment being to furnish means of varying, between wide limits, the conditions of temperature and pressure, and of gaseous or liquid environment, in which the metallic vapors emit their characteristic radiations. By setting at the proper angle a plane mirror, mounted at the center of the table, light from any source can be reflected to a concave mirror, which forms an image of the source on the slit of a large concave grating spectrograph. The most extensive single investigation made in this laboratory was a study of the spectrum of the spark in liquids and compressed gases, to test Wilsing's pressure theory of temporary stars.

In the diversified work of the Yerkes Observatory the desire to attack the problem of stellar evolution in the most effective manner was not forgotten. Experience with the

large concave grating of the Kenwood Observatory had furnished convincing evidence of the advantages of fixed instruments mounted on piers, and the beautiful resolution of the solar spectrum with this apparatus made observations of stellar spectra with small prism spectroscopes seem unsatisfactory. It was felt from the first that every effort should be made to devise a telescope capable of bringing a large and well-defined solar image, or a sharp and brilliant stellar image, into a laboratory, where it could be observed to the best possible advantage, with appliances too large or too heavy for use with moving telescopes. It seemed clear that, if this desire could be realized, and if the full advantages of reflecting telescopes for astrophysical research could be attained, the means thus provided should render possible a well-directed attack on the problem in mind.

The work of the Rumford spectroheliograph showed that the further development of this instrument must involve a considerable increase in dispersion, so as to permit the use of the narrower dark lines. This meant an instrument of large dimensions, necessarily to be mounted in a fixed position, since it could not be attached to a moving telescope tube. Another piece of work pointed to the same requirement. At the Kenwood Observatory attempts were made to photograph the spectra of sun-spots, and negatives were secured showing a few of the more conspicuous widened lines. The need of a larger solar image for this work was met by the Yerkes telescope. A marked improvement in the photographs resulted. However, it was clear that photographs of spot spectra suitable for the most refined investigations could not be obtained without the use of a spectrograph of much higher dispersion. For satisfactory results a spectrograph of at least 10 feet focal length was needed, and this could not be attached to the moving telescope tube. Here, again, was another argument for the fixed type of telescope.

The work of constructing such an instrument was accordingly taken up. The original purpose of building a heliostat was modified, through the recognition of the superior advantages of the coelostat, introduced by Turner for eclipse observations. A 30-inch coelostat, designed by Ritchey, was constructed in the instrument shop of the Yerkes Observatory. This was destroyed by fire, but a gift from Miss Snow of Chicago, in memory of her father, provided the funds required for the Snow telescope. In the preliminary tests of this instrument at the Yerkes Observatory the images were not very satisfactory, but it subsequently gave admirable results at Mount Wilson.

In establishing the Carnegie Institution at Washington, Mr. Carnegie gave expression to his appreciation of the fact that some of the most fundamental needs of scientific research could not be supplied by existing agencies. As a rule, a university must build its observatory or biological laboratory near at hand, rather than at a site chosen because of atmospheric advantages or the richness of the local fauna and flora. Its funds, usually given for specific purposes, are likely to be unavailable, or perhaps inadequate, to provide a sufficiently large corps of investigators, devoted to research. If, through the efforts of one of its faculty, a new and promising instrument is projected, the trustees may not be in a position to supply the financial means required to construct it. Such conditions result from the very nature of a university's work, and consequently affect, in some degree, the policy of even so progressive an institution as the University of Chicago, where the authorities strongly favor original investigation. The Carnegie Institution, devoted exclusively to the furtherance of research, is not thus hampered. It therefore came about that this new Institution, with the cordial co-operation of the University of Chicago, made provision for the continuation and development of the work set

on foot at the Kenwood and Yerkes Observatories. A committee, appointed to report on the advisability of establishing an observatory for solar research, and another observatory for observations of the southern heavens, favored both of these projects. A careful test of various sites in the United States and in Australia, made at the request of the committee by Hussey, led to the provisional selection of Mount Wilson (5,886 feet), near Pasadena in southern California, as the site for the proposed solar observatory. An appropriation, granted by the Carnegie Institution in 1904, furnished the means of sending an expedition from the Yerkes Observatory to Mount Wilson. The Snow telescope was erected on the mountain, in a new type of house especially designed for it. An instrument shop was established in Pasadena for the construction of the spectroheliographs and other apparatus required for use with the Snow telescope. In December, 1904, the Carnegie Institution decided to establish a solar observatory of its own on Mount Wilson. Through the courtesy of the authorities of the Yerkes Observatory and the University of Chicago, the Snow telescope was retained on the mountain, and has since been purchased by the Solar Observatory. The optical work on the 60-inch mirror, which was also acquired by the Solar Observatory, was resumed by Ritchey in the optical shop at Pasadena. He also designed the mounting for this telescope, and the work of constructing it was soon undertaken.

CHAPTER XIII

ASTRONOMICAL ADVANTAGES OF HIGH ALTITUDES

The recognition of the advantages of making astronomical observations at high altitudes goes back to the time of Newton, who wrote as follows in his *Opticks* (third edition, p. 98):

> If the Theory of making Telescopes could at length be fully brought into practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix'd stars. * * * The only remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds.

It will be observed from these remarks that a clear and transparent sky is not the only need of the astronomer. In their passage through our atmosphere the rays which are united by a telescope to form the image of a star traverse different paths, depending upon their color. For air, like water or glass, though in a less degree, is a refracting medium; i. e., a ray of light entering it is bent from its straight course, and the amount of its bending depends upon the color of the ray, just as in the case of a prism. Violet light suffers the greatest refraction, and red light the least. Obviously, then, rays of different colors coming to a telescope from a star do not pursue the same path. Since the degree of refraction depends upon the temperature of the air, and since, under ordinary conditions, the temperature is changing in an irregular manner, we thus see why a star twinkles and undergoes rapid change of color. For the red rays may be momentarily reduced in brightness, through a change in

refraction of the air through which they pass. The star would thus appear blue for the time being. The next instant the intensity of the blue light might be reduced, causing the star to seem red. Since the length of the light-path and the degree of refraction increase toward the horizon, the twinkling of stars, which frequently disappears altogether at the zenith, is most apparent at low altitudes.

As the effect of twinkling is so apparent to the eye, it is easy to see that it may be greatly magnified in a telescope and produce serious interference with observations. The star image, instead of being a minute, sharply defined point, usually appears in the telescope enlarged, confused, and tremulous. The component members of close double stars, though easily within the resolving power of the telescope, under such conditions may overlap and appear as one. Similarly the minute surface details of the Moon or planets may be entirely obliterated by atmospheric disturbance. It is as though the astronomer were forced to observe the heavenly bodies from the bottom of an ocean, not calm and tranquil throughout its mass, but constantly disturbed by currents of various directions and at different depths, and by irregularities of density arising from unequal temperatures.

It sometimes happens that excellent definition of telescopic images is obtained through smoke or haze, under circumstances which might appear to be wholly unsuitable for astronomical work. For certain kinds of observations, where perfect definition is all important and brightness of the image of less consequence, the lack of transparency occasioned by hazy air does no harm. But in most classes of work particles suspended in the atmosphere not only reduce the intensity of the light, but produce serious interference through scattering of the rays. The brightness of the sky near the Sun, for example, increases greatly with the number of dust or smoke particles in the air. In visual observations of the

details of sun-spots this might not be harmful; but the visibility of the prominences is seriously reduced when they are seen against a brilliant background of sky. The brightness of stars is also much affected by haziness of the atmosphere.

Even on a clear and transparent night the stars are less brilliant at sea level than when seen from the summit of a high mountain. For the air itself is a powerful absorbing medium and reduces, more than we ordinarily realize, the brightness of objects seen through it. Illustrations of the relative advantages of photographing stars at altitudes of 1,200 and 6,000 feet respectively is given in Plates LVI and LVII.

The difficulties in astronomical observations arising from atmospheric disturbances increase with the aperture of the telescope employed. This is because the rays falling on opposite sides of a large object-glass traverse more widely separated paths than those united by a small object-glass. They are thus liable to greater atmospheric disturbance, on account of the difference in the conditions governing the refraction of the light along the two paths. The disturbances of the air take the form of more or less regular waves. With an aperture which is small compared with the length of one of these waves, the effect on the image might not be great. If, however, several waves were included within the aperture, the confusion might be very marked indeed. Hence large telescopes require better conditions than small ones.

In selecting the site of the Yerkes Observatory, practical considerations necessarily limited the choice. It was essential that the observatory should be situated within easy reach of the university, and this fact rendered it impossible to consider seriously the favorable mountain regions which were known to exist in the extreme western part of the United States. The chosen site has many advantages over points in the immediate neighborhood of Chicago. The absence of smoke

and the brilliant illumination of the sky produced in large cities by electric lights, the freedom from vibration arising from railways and the heavy traffic of a large city, and the facilities for quiet study afforded by the tranquil life of the country, were important recommendations of the Lake Geneva site. The observational work of the Yerkes Observatory has been sufficient in amount and quality to show that more valuable material can be secured under such atmospheric conditions than can be adequately discussed without a far larger staff of computers than the observatory has ever been able to employ. It goes without saying, however, that a better site would have been preferable.

But it must not be supposed, from what has been said, that all mountain peaks would make good observing stations. It is true that by ascending into the upper atmosphere the astronomer may escape the strong absorption exercised by the dense air of lower levels. As one goes up, the stars become brighter and brighter, especially near the horizon, since the decrease in length of path is much greater in this region than near the zenith. Blue and violet light suffer more from atmospheric absorption than the red, yellow, and green rays. For this reason, the advantages of high elevations, so far as transparency is concerned, are more apparent in photographic than in visual observations, since the blue and violet rays are principally concerned in the production of the photographic image.

Thus, from the standpoint of atmospheric transparency, mountain sites may always be considered to possess advantages for astronomical work. But transparency is almost invariably a much less important consideration than sharpness of definition, which does not, by any means, depend merely upon altitude. In the first place, the geographic location of the mountain in question is a most important factor. Long periods of continuous clear weather, enjoyed

in certain favored regions, are accompanied by. a uniformity of atmospheric conditions unknown in countries where storms usually prevail. It is not merely that clouds and rain are less common; for, if this were the only important consideration, a clear night in one part of the world might be as good for astronomical purposes as an equally clear night in another. In a region of storms the disturbances follow one another so rapidly that during the intervening periods of clear weather the atmosphere rarely has time to settle down to a calm, homogeneous state. In southern California, for example, the sky is almost constantly clear for many months in the year, and the uniformity of the atmosphere is shown by the steadiness of the barometer and the low average wind velocity. During the rainy season, however, when storms may recur in rapid succession, the atmosphere in such a region is disturbed, and the conditions for astronomical work on the beautifully transparent nights that intervene between storms are frequently no better than in the eastern part of the United States.

Pike's Peak (14.147 feet) affords an example of a mountain site poorly adapted for astronomical purposes. In June and July of 1893 I spent two weeks there, in company with Keeler, engaged in an attempt to photograph the solar corona without an eclipse. Under normal conditions the sky, as seen from the peak, is of a deep blue by day, and very transparent by night. The conditions, therefore, are favorable for work in which transparency is the only important consideration. Thus Pike's Peak might serve very well for the measurement of the solar radiation, were it not for the fact that during the summer months (always the most important season for solar work), the mountain is frequently capped by clouds through a considerable part of the day. On many of the nights during our stay the sky was perfectly clear, and remained so until about nine o'clock in the morn-

ing. Then small cumulus clouds would begin to form immediately around the peak, and by noon a thunderstorm would be raging, frequently accompanied by a light fall of snow. In these storms the wind rose to a tremendons velocity, sometimes as great as seventy miles an hour, and the electrical phenomena were very remarkable. The frequency with which these storms cut off all solar observations, except in the early morning, illustrates the fact that even for work on the solar radiation, which requires a clear and transparent sky through the greater part of the day, Pike's Peak would serve but poorly, at least during this season of the year. As many of these storms were confined to the immediate summit of the mountain, a station several thousand feet below would probably offer more opportunities for work than the peak itself.

But this is not all. The definition of the Sun or stars is rarely good on Pike's Peak. This is probably due, not merely to frequent storms and high wind velocities, but also in part to the fact that the summit of the mountain is bare and rocky, so that heated currents of air rise from the surface and ruin the definition of the solar image. At this altitude mountain sickness is also very common, and would undoubtedly interfere, in some degree, with the operation of an observatory. The observers at that time stationed there by the Weather Bureau informed us that they could not remain on the mountain for long periods without impairment of health and energy. Two-thirds of the tourists who came to the summit, by the railway or on foot, were visibly affected by the high altitude. Another cause of difficulty at the time was forest fires in the mountains surrounding the peak, which sent volumes of smoke into the air. This rose to a great altitude and destroyed the deep blue of the sky.

The unsuccessful attempts to photograph the corona were renewed on Mount Etna in July, 1894, through the kindness of Professor Riccò, director of the Bellini Observatories

of Catania and Mount Etna. Our party, consisting of Professor Riccò, Signorina Riccò, Antonino Capra, mechanician of the observatories, Mrs. Hale, and myself, left Catania on July 7. After a drive of three hours we arrived at Nicolosi, where we spent the night. The following extracts from my diary relate mainly to the atmospheric conditions encountered:

July 8. Left Nicolosi at 6 A. M. Arrived at Casa del Bosco (4,760 feet) at $8^{h}\ 30^{m}$. Examined sky frequently, and found slight decrease of white as we ascended. Crossed lava stream of 1892, and had excellent view of the craters of that year, the latest of which still emits vapor. Arrived at the observatory (9,650 feet) at $1^{h}\ 35^{m}$. The temperature had fallen to 9° C., and the sky was nearly covered with clouds. Half an hour later we were enveloped in cloud, which surrounded us until evening, when sky was whitish, with marked halo around Moon. Stars unsteady, even in zenith.

July 9. Sky clear, with strong wind blowing the smoke from the great crater (which rose behind the observatory to an altitude of 10,900 feet) away from the direction of the Sun. Half the island of Sicily was dimly visible from the observatory through a great brown bank of thick haze, the upper surface of which seemed to be nearly on a level with us. Cumulus clouds commenced to form at 9^{h}, and soon the sky was nearly covered. At 12^{h} the Sun was seen between passing clouds to be surrounded by a bright halo. Wind changed to west in the afternoon, and sky became much whiter.

July 10. Wind blew smoke of great crater over Sun, making sky very white. Observed Sun with Professor Riccò by projection with 12-inch telescope. Image rather better than at Catania, but became unsteady later. At 10^{h} some small cumulus clouds had formed, and Sun was surrounded by bright halo. Clouds of insects were also noticed in direction of Sun, as on Pike's Peak. Observed prominences with Professor Riccò, but images were no better than at Catania. At sunset watched shadow of Etna from the Torre del Filosofo. Whole sky covered with dense haze.

July 11. Sky very white, bright ring around Sun. Observed atmospheric lines with direct-vision spectroscope. Balanced telescope, and observed Sun by projection. Seeing excellent; granulation, spots, and faculae well defined. Strong odor of sulphur. At

sunset visited Valle del Bove. Sky filled with haze, and almost too bright for the eye 10° from Sun.

July 12. Sky very white. Wind still blowing smoke from crater over Sun. Bank of haze above level of observatory. Observed Sun by projection with Professor Riccò; image unsteady. Climbed to top of crater, and found sky in zenith of deeper blue than when seen from observatory. Whole island enveloped in haze. Descended to observatory by moonlight; double halo around Moon. Observed Moon, Saturn, and several stars with the 12-inch, using powers up to 430. Seeing magnificent; images almost perfectly steady with highest power. Both Moon and Saturn were very low, but images were remarkably good. With naked eye scintillation was hardly perceptible in stars higher than 30°.

July 13. Wind blowing from direction of crater, but sky best since July 9: cloudless and generally whitish, but increase in brightness toward Sun was gradual. Much dust. Telescope in use until $9^h\ 40^m$ by Professor Riccò for daily record of chromosphere. Prominences very well seen. At $9^h\ 50^m$ broad and brilliant ring of whiteness around Sun, making it useless to try for corona. Smoke blowing directly over Sun, and diffusing through entire sky. Solar image observed by projection; definition very poor. At 11^h sky had improved, and preparations were made to photograph corona, but five minutes later more smoke blew over Sun, and sky became very white. Mirror found to be dewed, and surface badly tarnished by the sulphurous fumes, though it had been tightly covered every moment it was not in use. Sky around Sun remained bright, and wind was so violent that no photographs could be made. Strong sulphurous odor.

July 14. Smoke blowing across sun. Strong sulphurous odor. Whole eastern sky white. Prominences fairly well seen at $7^h\ 45^m$. Left observatory at 3^h, and arrived at Catania about midnight.

As I was assured by Tacchini and Riccò that the sky is frequently very clear on Etna, it may safely be concluded that the difficulties we encountered were exceptional. During the entire time of our stay in southern Italy and Sicily the atmosphere was very hazy, and the sky was rarely of a deep blue. I was told by Galvagno, the custodian of the Etna Observatory, that the smoke this year was much more notice-

able than usual. If the wind had blown it away from, instead of toward, us, the sky would probably have been pure, though hardly as blue as when seen from Pike's Peak during the first part of our visit there.[1]

So much for the results of brief personal experience in Sicily and the Rocky Mountains. From the standpoint of a solar observer requiring fine definition, they do not appear very encouraging. Moreover, conclusions reached by other astronomers have been equally unfavorable to Colorado air; and we find Piazzi Smith, in his book *Teneriffe: An Astronomer's Experiment*, reporting but very little good solar definition at altitudes up to 10,700 feet on a tropical island. His expedition to Teneriffe in 1856, made for the express purpose of testing the atmospheric conditions on a mountain-peak, was the first serious study of this kind. The transparency of the air and the definition of the stars by night were found to be excellent; but high winds, dust in the upper atmosphere, and unsteady solar images were also encountered.

However, good solar definition is experienced on Mont Blanc (15,780 feet), at the Kodaikanal Solar Observatory in India (7,700 feet), and at the Pic-du-Midi in France. There is obviously no incompatibility between high altitudes and good solar definition. The poor definition reported by various observers on mountain-peaks is due either to the prevalence of storms or to local disturbances, caused by warm air rising from the heated summits of mountain-tops protected by little or no foliage. At Mount Hamilton, where the night conditions are so favorable, the slopes immediately around the summit are composed of bare rock, which becomes intensely heated and necessarily affects the solar definition. This is a matter of no special consequence to the Lick

[1] The attempts to photograph the corona were continued by Riccò under better conditions, but neither this method nor any other has yet proved successful.

Observatory (Plate XLVIII), since the work is confined to night observations. The great number of admirable results, many of them requiring the finest definition, which have been obtained at the Lick Observatory, afford the best of evidence that its site was well chosen.

The results of experience in various parts of the world would seem to indicate that a mountain observatory, if it is to enjoy good conditions both by night and by day, should be situated in a climate where the sky is clear continuously for periods of several weeks or months, and the average wind velocity is low. The summit of the mountain, as well as its slopes, should be covered with foliage, to protect it from the heat of the Sun. Finally, the elevation should be sufficient to escape the dust which diffuses itself through the air in the dry season, and the low-lying fogs and clouds frequently encountered in regions near the sea.

CHAPTER XIV

THE MOUNT WILSON SOLAR OBSERVATORY

FROM the preceding chapters, it will be seen how the plan of research of the Solar Observatory was developed. At Kenwood a programme of solar observations, involving the use of the spectroheliograph, the photographic study of the spectra of Sun-spots and other solar phenomena, and the fullest possible application of laboratory methods in astrophysical research, was instituted. At the Yerkes Observatory this programme was broadened and extended, in the hope of providing ultimately for the general study of stellar evolution; the possibilities of the spectroheliograph were more fully realized, through the advantages offered by the 40-inch refractor; and instruments better adapted than the large refractor for the further prosecution of the work, such as the Snow telescope for solar research, and the 60-inch reflector for stellar investigations, were designed and partially or wholly constructed. After this period of preparation, devoted in large part to the development of plans and methods, the Mount Wilson Solar Observatory was organized for the study of stellar evolution, at a station enjoying the best climatic advantages.

In brief, the scheme of research of the Solar Observatory comprises: (1) solar investigations, to contribute toward our knowledge of the Sun (*a*) as a typical star and (*b*) as the central body of the solar system; (2) photographic and spectroscopic studies of stars and nebulae, bearing directly upon the physical nature of these bodies, with special reference to their development; (3) laboratory investigations, for the interpretation of solar and stellar phenomena. With

the central problem in mind, each successive research is designed to occupy a logical place in a concentrated attack, proceeding along these converging lines.

The variety of the problems connected with the establishment of the Solar Observatory on Mount Wilson affords a good illustration of the diversified work of an astronomer. It was necessary, in the first place, to test the atmospheric conditions by means of telescopic and meteorological observations extending over a considerable period of time, in order to make certain that the site would prove suitable. In the second place, since the summit could be reached only by a narrow mountain trail, it was evident from the outset that the question of transporting building materials and the parts of heavy instruments would not be an easy one to solve. Again, since one of the prime purposes of the new observatory was to take advantage of the possibilities of improved instruments, the design and construction of the telescopes, spectroscopes, and other appliances would require the solution of many instrumental and engineering problems, and much work of experiment. It was known, for example, that glass mirrors change their form decidedly when exposed to the Sun's rays. For this reason it was to be feared that they might not give good solar images. This is a matter of fundamental importance, since the fixed telescope for solar observations necessarily involves the employment of mirrors. In addition to these questions, many others, very diverse in character, presented themselves. These included the preparation of a programme of research, adapted for the special requirements of the new observatory, in which all the investigations in progress were to be closely correlated; the consideration of the best methods of discussing and interpreting the photographs made with the spectroheliograph and other instruments; the invention and construction of special measuring and computing machines, etc.

From a meteorological standpoint, the state of California may be divided into three parts. In the northern region the rainfall is very considerable, much cloudiness prevails, and in almost all respects the conditions are unfavorable for astronomical work. The central region, which may be considered to extend as far south as Point Conception, is favored with much better weather conditions, best exemplified at the Lick Observatory, on Mount Hamilton, where a high average of night-seeing is maintained during a large part of the year. In the southern part of California the climatic conditions are different from those which prevail in the two other sections of the state. The lighter rainfall is naturally associated with fewer clouds, a remarkably steady barometer, and very light winds.

There can be no doubt that the character of the country immediately adjoining an observatory site affects the conditions for astronomical work to an important degree. For this reason it became desirable to make preliminary tests of a considerable number of points in southern California. Similar tests might have been desirable in Arizona, were it not for the thunderstorms that prevail during the summer months in the vicinity of Flagstaff, and other promising localities, which would interfere so seriously with solar work as to put this region almost entirely out of consideration. As there were other serious objections to Arizona sites, and as Hussey's tests at Flagstaff did not indicate that the conditions were as favorable as in California, attention was concentrated on the relative claims of various mountains in southern California.

Hussey's tests in this region included Echo Mountain, Mount Lowe, and Mount Wilson, in the Sierra Madre range, and Cuyamaca and Palomar, much farther to the south. His observations seemed to leave no doubt that Mount Wilson would prove to be the best site for the purposes of a solar observatory.

Mount Wilson is one of many mountains that form the southern boundary of the Sierra Madre range (Plate XLIX). Standing at a distance of thirty miles from the ocean, it rises abruptly from the valley floor, flanked only by a few spurs of lesser elevation, of which Mount Harvard is the highest. Except for a narrow saddle, Mount Wilson is separated from Mount Harvard by a deep cañon, the walls of which are very precipitous. Farther to the west, beyond the saddle leading to Mount Harvard, the ridge of Mount Wilson forms the upper extremity of Eaton Cañon, which leads directly to the San Gabriel Valley. East and north of Mount Wilson lies the deep cañon through which flows the west fork of the San Gabriel River, and beyond this rise a constant succession of mountains, most of them higher than Mount Wilson, which extend in a broken mass to the Mojave Desert. The Sierra Madre range forms the northern boundary of the San Gabriel Valley, which is further protected toward the east from the desert by the high peaks of the San Bernardino range.

The view from the summit of Mount Wilson is most extensive, embracing the whole of southern California, and reaching out over the Pacific to islands nearly one hundred miles distant. Cuyamaca, about 130 miles to the south, not far from the Mexican boundary, is easily visible. San Bernardino and San Jacinto peaks, the latter 90 miles away, are so distinctly seen under normal conditions that a station might easily be established on either of them, for experiments in measuring the velocity of light from Mount Wilson. Mount San Antonio (10,080 feet), 25 miles away, has already served as a station for certain observations of the solar radiation, supplementing the work of the Smithsonian Expedition at Mount Wilson (Plate L).

During a part of the year, particularly from April to August, fog rolls in from the ocean and covers much of the

San Gabriel Valley during the night (Plate LI). But these fog-clouds rarely attain elevations exceeding 3,000 feet. The mountains of the Sierra Madre range rise high above the fog, and during many months of the year they enjoy practically continuous sunshine. In summer the sea breeze blows for a part of the day, but it attains only a low velocity, which decreases in passing from the valley to the mountain tops.

Mount Wilson is reached from the San Gabriel Valley by either one of two trails. One of these, known as the "Wilson Trail," ascends from Sierra Madre, and is steep and irregular. The other, called the "New Trail," rises from the foot of Eaton Cañon, abont 6½ miles from Pasadena, and is about 9¼ miles long. When our work commenced, it was but little over two feet in width at its narrowest parts. It has an average grade of about 10 per cent., and is much better adapted for transportation purposes than the old Wilson Trail.

Some hundreds of tons of building material for the observatory have been taken over the New Trail, on the backs of mules or "burros" (donkeys) (Plate LII). The heavier parts of instruments, which could not be taken up in this way, were carried on a special truck built for the purpose (Plate LIII). The running-gear consists of four automobile wheels with rubber tires. The body of the truck is hung by wrought-iron yokes from the running-gear, with its lower surface at a height of only six inches above the ground. Steering-gear, of the type used on automobiles, is provided for both pairs of wheels. A man riding on the load steers the forward wheels, while the rear wheels are steered with a tiller by a man walking behind the carriage. A single large horse pulls a load of a thousand pounds on this carriage without difficulty. With two horses, used in relays, the trip from the lower end of the trail to the summit and return is completed with such a load in about fifteen hours. About sixty

round trips were made with this truck for the purpose of carrying the mirrors, lenses, and heavy castings of the Snow and Bruce telescopes, the parts of a 15-H. P. gas engine, and other heavy machines, as well as the 4-inch pipe columns used in constructing the steel skeleton of the Snow telescope house.

During the first two years, it was hoped that a railway would be constructed to the summit of the mountain, where a hotel had already been erected. When it finally appeared that this hope must be abandoned, we were compelled to adopt the alternative of widening the New Trail into a wagon-road (Plate LIV). This work, which was done during the autumn and spring of 1906 and 1907, was considerably hampered by unprecedented storms in December and January. The snow on the summit of Mount Wilson (Plate LV) was five feet deep on a level, and the torrential rains, below the snow line, brought down thousands of tons of earth and rocks from the steep slopes of the mountain. When these difficulties had been overcome, the transportation problem was so far solved as to permit the structural steel for the building and dome of the 60-inch reflector to be hauled to their destination.

Our systematic tests of the atmospheric conditions on Mount Wilson began in March, 1904. An old log cabin, which had been in a state of partial ruin, was rendered habitable and occupied until the "Monastery" was completed, in the following December. Frequent tests of the solar definition were made with a $3\frac{1}{4}$-inch refracting telescope, supplemented by meteorological observations.

The specific requirements of a site for an observatory to be devoted to solar research and the study of stellar evolution are as follows:

1. Excellent definition of the solar image, on many days of the year.

2. Excellent definition by night, so as to permit reflecting telescopes of large aperture to be used for the most exacting work.

3. Great transparency of the day and night sky, essential for accurate determinations of the "solar constant" (the total heat radiation of the Sun, at a point outside of the Earth's atmosphere), and the photography of stars and nebulae requiring very long exposures.

4. Continuous clear weather for periods of many weeks, rendering possible daily observations of changing phenomena, of which an imperfect or erroneous idea might be derived from scattered observations.

5. A low average wind velocity, especially during the best observing season, to insure freedom from vibration of telescopes employed for photographic work.

It is easy to see why the definition of the Sun's image is usually much inferior to that of the stars or planets. The heating of the earth, caused by the Sun's rays, produces currents of warm air, which rise and mix with the cooler air above. It has already been explained that poor definition is produced by irregular refraction in the atmosphere, and that this is caused by irregularities in the temperature of the air through which the light rays pass. In this respect a mountain peak may have some disadvantages as compared with an extensive level area, because the rising currents of warm air follow the mountain sides and tend to produce marked disturbances in the images observed from the summit. It is evident that this effect will be greatly enhanced if the mountain is bare and rocky, instead of having its slopes covered with trees and bushes. As the latter condition prevails on most of the slopes of Mount Wilson, the heating of the air is much less pronounced than in the case of many other mountains. It is nevertheless very noticeable, and for this reason the best observations of the Sun are made one or two

hours after sunrise, and about the same time before sunset. It is true that great depths of atmosphere must be traversed by the Sun's rays when it is so near the horizon. Nevertheless, the image on a large number of days in the summer season is wonderfully sharp and distinct, permitting the finest details of structure to be observed. The conclusions based upon observations made with the $3\frac{1}{4}$-inch refractor were afterward confirmed with the large aperture of the Snow telescope, leaving no doubt that with respect to solar definition Mount Wilson offers very exceptional advantages.

The tests of the night definition, and of the transparency of the night sky, were made by Barnard, during the work of the Hooker Expedition. In chap. v a description has been given of the Bruce 10-inch photographic telescope of the Yerkes Observatory, used by Barnard in his studies of the Milky Way. In order to extend farther south the work previously done with an instrument of 6 inches aperture on Mount Hamilton, Barnard brought the Bruce telescope to Mount Wilson and made with it a remarkable series of photographs. Mount Wilson (latitude $+34° 13'$) is 8° south of the Yerkes Observatory, and 3° south of the Lick Observatory. This fact, combined with the great transparency of the sky, permitted Barnard to photograph regions of the Milky Way which had been out of reach in his earlier work.

The best way of comparing the transparency of the sky at Lake Geneva and Mount Wilson is by taking two photographs of the same region of the heavens, with the same exposure time, on photographic plates of the same sensitiveness, used with the same telescope, by the same observer. Such a comparison is illustrated in Plate LVI, which represents the cluster *Messier 35*. The difference in the number of stars included on the photograph is a striking illustration of the advantages of Mount Wilson. Indeed, if this result were not confirmed by many others, and regarded by Barnard

as representing a fair relative test, it might be supposed that some difference in the mode of development or in the sensitiveness of the plate had entered. The night on which the Mount Wilson photograph was made was an average summer night, while in the case of the Yerkes Observatory photograph the transparency was possibly higher than the average there.

An illustration of the same sort is given in Plate LVII, which shows the *Pleiades* as photographed by Barnard with the Bruce telescope, with an exposure of 3 hours and 48 minutes at Mount Wilson and 9 hours and 47 minutes at the Yerkes Observatory. It will be seen that the first photograph shows quite as many stars as the second, and also has a great advantage in sharpness, as indicated by the much larger amount of detail brought out in the nebulae. This is due to the fact that the greater diffusion of light in the Wisconsin sky tends to obliterate the finer details of the photograph. It is interesting to conjecture what advantages will result from the use of the 60-inch reflector under these fine conditions.

During the long exposures Barnard kept a star on a pair of cross-hairs in the eye-piece of a 5-inch refractor, attached to the Bruce telescope. In this way he observed the definition of the stellar images on a large number of nights. As previously explained, the definition of a star does not depend in any considerable degree upon the transparency of the atmosphere, but rather upon the absence of irregular refraction. Barnard found the average night "seeing" to be remarkably good, and this conclusion has also been confirmed with the large aperture of the Snow telescope.

The transparency of the sky by day has been most thoroughly tested by Abbot, in his studies of the "solar constant" of radiation, which are described in chap. xxii. As compared with Washington, where the previous work

of the Smithsonian Astrophysical Observatory has been done, the advantages of Mount Wilson are very marked. Of equal importance for this work is the fact that the observations can be made day after day, with practically no interruption, for a period of many weeks. In Washington, during the same period, it might be possible to obtain only two or three trustworthy determinations. Thus the manner in which the solar radiation varies can be shown, in the one case, by its daily fluctuations, while in the other it might be wholly concealed.

Finally, the average wind velocity in the dry season proved to be extraordinarily low, not only for an exposed mountain-peak, but as compared with a station at any level. During the rainy season, when there is much cloudy weather, violent storms, accompanied by high winds, are not uncommon. But in the dry season an almost dead calm frequently prevails at night, and also during the early morning solar observations. In the later hours of the day there is usually a light breeze. The typical condition on Mount Wilson during the dry season may be described as a perfectly cloudless sky, and so little breeze that the leaves are hardly stirred by it.

It would be tedious to discuss the other conditions, such as the heavy growth of foliage, the presence of abundant springs of water, the neighborhood of large cities, etc., which contribute toward the advantages of Mount Wilson as an observatory site. The astronomical tests have been described in detail because they illustrate the practical bearing of atmospheric conditions on astronomical observations.

CHAPTER XV

THE SNOW TELESCOPE

LÉON FOUCAULT appears to have been the first to appreciate the advantages of a fixed telescope, capable of forming a solar or stellar image within a laboratory. A large *siderostat*, constructed by Eichens after his designs, was completed in 1868, the year of Foucault's death. It remained at the Paris Observatory, where it was subsequently employed by Deslandres for solar photography. For small images of the Sun this instrument gave good results, although the imperfection of the driving caused the image to wander more or less from a fixed position. This difficulty has been inherent in almost all types of fixed telescopes. It is coupled with the inconvenience that the solar image produced by the siderostat or heliostat rotates in an irregular manner, which would cause distortion in long-exposure photography with a fixed spectroheliograph.

It is not easy to see why the heliostat, in some of its forms, was not more rapidly developed. With a few exceptions, its practical application has been confined to small heliostats of various types, used to reflect a beam of sunlight into the laboratory, but not to produce a large image of the Sun. In other words, the heliostat was not developed into an instrument of precision, capable of giving a large and well-defined solar image, and maintaining it accurately fixed in position, until the *coelostat* was revived for eclipse purposes, about ten years ago.[1] This instrument had been invented long before, but its great advantages, due to the

[1] The great *equatorial coudé* of the Paris Observatory is an admirable example of a fixed telescope, but I do not think it has been tested for solar observations.

simplicity of its construction, the ease of driving it with a precision as great as in the case of the equatorial refractor, and, above all, the fact that the solar image produced by it does not rotate, had been overlooked. At Turner's suggestion it was employed for eclipse purposes, at first by some of the English parties, and subsequently by astronomers in all parts of the world.

However, the conditions under which eclipse observations are made are very different from those that obtain in ordinary solar work. A defect of the coelostat is that the direction of the beam of light reflected horizontally from the mirror varies with the declination of the Sun. During the few minutes of a total eclipse the Sun's declination does not change appreciably, and the telescope into which the light is reflected by the coelostat stands fixed in position. But in solar observations continued throughout the year the direction of the reflected beam is constantly changing, as the Sun moves north or south of the equator. As it would be inconvenient to swing the long telescope tube, which is pointed at the coelostat, around through the necessarily large angle, a second mirror must be introduced to receive the light reflected from the coelostat mirror and send it in any desired direction. About once a week, or sufficiently often to cause no appreciable loss of sunlight, the second mirror is moved a short distance, so that it may continue to receive all the light of the reflected beam, in the changed position given it by the variation in the Sun's declination.

Another difficulty of the coelostat, which is common to all forms of heliostat, but plays no part in total-eclipse work, is the distortion of the mirrors by sunlight. This obstacle is really the only serious one presented by this form of telescope. How it has been met at the Solar Observatory is explained below.

The Snow telescope, the optical and mechanical parts of

which were constructed under Ritchey's supervision in the shops of the Yerkes Observatory, is illustrated in Plate LVIII. This photograph shows the coelostat and the adjustable second mirror, whence the light is reflected to a concave mirror of 60 feet focal length, which forms the solar image. The general arrangement of the telescope, as established on Mount Wilson, is indicated in Fig. 5. The coelostat stands

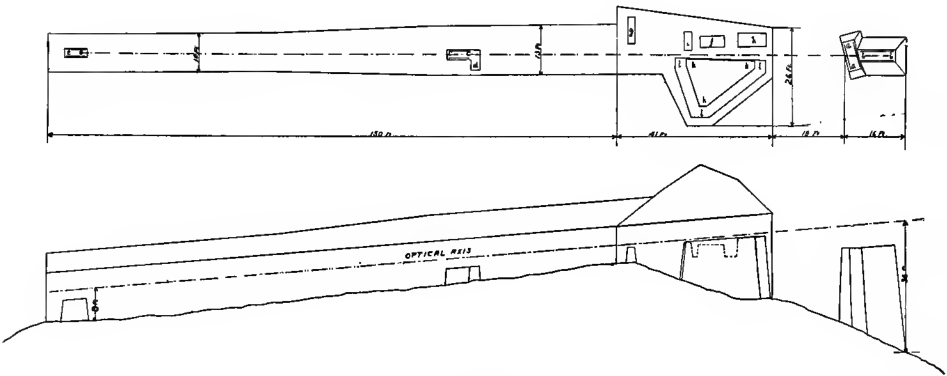


FIG. 5
Plan and Elevation of Snow Telescope House on Mount Wilson

on a carriage, which can be moved east or west along the line *aa*. On account of the configuration of the ground, which falls rapidly toward the north, it was necessary to make the long axis of the building run 15° east of north, instead of being exactly in the meridian. For the same reason this axis is not horizontal, but inclined downward 5° toward the north. Without these adaptations of the plan to the conditions of the site, the height of the northern part of the building would have been very great, involving serious increase of expense. The rails *bb*, on which the carriage bearing the second mirror slides, are parallel to the optical axis. The coelostat mirror, 30 inches in diameter, and the second mirror, 24 inches in diameter, have plane surfaces,

and serve merely for bringing the sunlight into the telescope house. The plane of the coelostat mirror is parallel to the Earth's axis, and the mirror can be rotated around this axis once in forty-eight hours, by means of a driving-clock. This exactly counteracts the motion of the beam due to the Sun's apparent motion through the heavens.

From the second mirror the light passes to either one of two concave mirrors, each 24 inches in diameter (Plate LIX). One of these, which has a focal length of 60 feet, is supported on a carriage so that it can be moved (for focusing) along the rails *cc*, which are mounted on the small pier shown near the middle of Fig. 5. This mirror produces an image of the Sun about 6.7 inches in diameter, at a position in the spectroscope house determined by the angle which the concave mirror makes with the incident beam of sunlight. If the mirror stood normal to the beam, the sunlight would be reflected directly back upon itself toward the second mirror. If, however, the concave mirror is turned slightly to one side, the solar image can be formed at the end of the pier *f*, where the 5-foot spectroheliograph stands. By moving the mirror back toward the north, along the rails on which it slides, the image can be brought to a focus on the pier *i*, where the slit and photographic plate of a Littrow spectrograph, of 18 feet focal length, are mounted. Again, by rotating the concave mirror so as to return the beam in a somewhat different direction, the solar image can be sent into the constant temperature room *lll*, where the bolographic apparatus, for studying the heat radiation of different parts of the Sun, is mounted on the massive triangular pier *kkk*.

If a larger solar image is required, the mirror of 60 feet focal length is moved out of the way, and the beam from the second mirror allowed to pass to a concave mirror of 143 feet focal length, mounted on a pier at the extreme north end of the telescope house. The image of the Sun is then

formed at the pier g, 143 feet from the concave mirror. This image is 16 inches in diameter, and is used for the special study of solar details, for which a large scale is required.

The remarkable convenience of such a telescope, when contrasted with a great movable refractor like the Yerkes telescope, is immediately evident. Instead of attaching each heavy instrument, one by one, to the end of a moving telescope tube, it is set up once for all on a pier, where its adjustments need never be disturbed. It is thus possible to pass rapidly from one instrument to another, photographing the forms of the calcium flocculi, for example, with the spectroheliograph, and their spectra, only a moment later, with the powerful Littrow spectrograph. In view of the importance of studying solar phenomena nearly simultaneously by various methods, and of closely correlating the observations, the advantages afforded by such a telescope will be easily recognized.

The peculiar form of house in which the Snow telescope is mounted calls for a word of explanation. In previous experiments, some of which were made on Mount Wilson in the spring of 1904, the conclusion was reached that the disturbance of the definition caused by warm air rising from the ground in the immediate neighborhood of the heliostat could be appreciably reduced by mounting the instrument at a considerable height. Observations made with a telescope supported in a tree, at various heights up to seventy feet, seemed to leave no doubt regarding this point. A second consideration, the importance of which had been particularly emphasized by experience with a smaller coelostat telescope, having a closed tube not provided with means of ventilation, was the necessity of designing a house so that the temperature within would be at all times as nearly as possible the same as that of the outer air. It is evident that,

if this condition is not met, the mixture of air of different temperatures at the open end of the house, through which the beam enters, will cause irregular refraction and consequent disturbance of the image.

Plate LX shows the pier on which the coelostat is mounted, at a height of nearly 30 feet above the ground. Since the parallel rays from the coelostat to the concave mirror pass through a closed house, it is not essential that that part of the building should stand high above the ground. It is important, however, that disturbances due to heating of the walls, caused by sunlight falling upon them, be obviated. For this reason all parts of the building, including the movable shelter, the spectroscopic laboratory, and the long narrow house extending north from the laboratory, have an inner wall and ceiling of canvas, and an outer wall composed of canvas louvers, very completely ventilated. The roof is also ventilated, by wooden louvers at the ridge throughout the entire length of the movable shelter and the north extension, and at the peak of the laboratory. Rain and snow are prevented from entering the roof louvers by means of canvas guards, which can be raised or lowered at will. The house extending north from the laboratory has a floor of canvas, with a space below, through which the air may pass freely.

The louvers surrounding the coelostat pier are intended to protect the pier from vibration caused by the wind, and from heating by the Sun. The steel structure does not touch the pier at any point, and is therefore made rigid enough to support itself in high winds. When not in use, the coelostat and second mirror are covered by a house on wheels, closed at both ends by walls of heavy canvas. These may be opened, so that when the house is moved to the north the coelostat stands fully exposed. The movable shelter then fits closely against the south wall of the laboratory, and forms a part of the tube through which the beam passes.

In the preliminary tests of the Snow telescope at the Yerkes Observatory the results were rather disappointing, though good images were sometimes obtained. There was evidence of distortion of the mirrors by the Sun's heat, and in the first experiments on Mount Wilson similar difficulty was experienced. Soon after the exposure of the mirrors to the Sun it was seen that the focal length was increasing, and, as the focus changed, evidence of astigmatism, due to the distortion of the plane mirrors, made itself apparent in the appearance of the image inside and outside of the focal plane. It was soon found that the focus changed much more rapidly after the mirrors had been silvered for some time, because of the greater absorption of heat by the slightly tarnished surfaces. Moreover, the change was less on a day with a cool breeze than on a day with no wind. The question then arose whether this difficulty could be remedied.

In the early morning, when, as before stated, the definition of the Sun is best, the heating is much less marked than later in the day. If the mirrors are shielded from sunlight between the exposures of photographs, and if the exposures are made as short as possible, excellent results can be obtained at this time, and in the late afternoon, not long before sunset. It has been found advantageous to direct a strong blast of air on the surfaces of the mirrors, by means of electric fans, during the exposures of the photographs and the intervals between them.

It must be understood that the precautions mentioned are necessary only when it is desired to secure the finest possible definition of the solar image. When such precautions are used, the average photographs taken during the summer in the early morning with the Snow telescope and a temporary spectroheliograph are but little inferior to the best photographs, secured on only a few days in the year, with the 40-inch Yerkes telescope and the Rumford spectroheliograph.

The best photographs taken on Mount Wilson are distinctly superior to the best secured in our work with the Rumford spectroheliograph. It must not be supposed that no work can be done with the Snow telescope except under the conditions stated. As a matter of fact, very fair photographs can be obtained with the spectroheliograph at almost any time during a cool day, and in the early morning and late afternoon hours of a hot day without wind. It is only necessary to arrange the daily programme of observations so that the spectroheliograph, which requires the finest definition, is used during the period when the seeing is best. Photographic work on the spectra of sun-spots follows, and after this is completed the conditions are entirely satisfactory for various other observations, such as bolographic work on the absorption of the solar atmosphere, etc. Some of the results obtained with the Snow telescope will be illustrated in subsequent chapters.

From laboratory tests, it appears that the distortion of mirrors in sunlight is chiefly due to actual bending of the glass, the front surface, expanded by the heat, becoming convex and the rear surface concave. Radiation from an electric heating coil, placed a short distance behind a mirror, restores its figure, but not perfectly. A much better way of heating the back of a mirror is by reflecting sunlight upon it. Perhaps the best plan, however, is merely to increase the thickness of the glass mirrors (p. 235).

CHAPTER XVI

SOME USES OF SPECTROHELIOGRAPH PLATES

THE necessity of designing the Rumford spectroheliograph for use as an attachment of the Yerkes telescope interfered somewhat with its efficiency. Under good conditions it gives excellent results, but the limitations of aperture, and the difficulty of securing perfect equality in motion of plate and solar image, are sometimes apparent in the photographs obtained with it. Fortunately, the case was different with the Snow telescope. It was possible here to adopt the most satisfactory form of spectroheliograph, in which the instrument is moved as a whole, while the image of the Sun and the photographic plate are stationary. The first spectroheliograph of this type was constructed in 1893 and employed in attempts to photograph the solar corona without an eclipse, from the summit of Mount Etna. For all instruments of moderate dimensions, motion of the spectroheliograph as a whole appears to be preferable to any mechanical contrivance for moving the plate and solar image in synchronism.

A photograph of the spectroheliograph, mounted for use with the Snow telescope, is reproduced in Plate LXI. A better idea of the general design may be obtained from Plate LXII, which shows the spectroheliograph in our instrument shop before it was completed. It consists essentially of a massive cast-iron base, bearing four short V-rails at its four corners, on which the moving part of the instrument is carried by four steel balls. The cast-iron platform which bears the slits and optical parts has four inverted Λ-rails, which rest on the steel balls, but almost its entire weight is supported by

mercury, in three tanks formed by subdivisions in the base casting. Wooden floats extend from the lower surface of the iron platform into these tanks, reducing to a minimum the amount of mercury (about 560 pounds) required to uphold the instrument. The motion of this platform with respect to the fixed solar image and photographic plate is produced by either one of two screws of different pitch, driven by an electric motor arranged to give a perfectly uniform speed.

The collimator slit, on which the solar image is formed, is shown on the right of Plate LXI. On account of the large size of the solar image, which is about 6.7 inches in diameter, the slit is $8\frac{1}{2}$ inches long. After passing through the slit the light falls upon a large collimating lens 8 inches in diameter, which renders the rays parallel. They then meet a silvered glass mirror, from which they are reflected to the two prisms, of $63\frac{1}{2}°$ angle. After being dispersed by the prisms the rays strike the 8-inch camera lens, which forms an image of the spectrum on the camera slit (shown near the center of Plate LXI). The optical train thus resembles that of the Rumford spectroheliograph, but the lenses and prisms are so much larger that no light is lost from the circumference of the solar image.

On account of the great curvature of the spectral lines produced by such prisms, it would be necessary to employ a highly curved camera slit, in case an ordinary straight slit were used to admit the light from the Sun. In this event the resulting photograph would be greatly distorted, because points lying along a straight line on the Sun would appear along a curved line in the photographs. Thus the image, instead of being circular, would be shaped somewhat like an apple, greatly flattened on one side. By dividing the curvature evenly between the two slits the distortion is eliminated and the photograph is made circular.

The actual operations in making a photograph of the flocculi with one of the calcium lines are as follows: An electric arc, the carbons of which have been moistened with a solution of calcium chloride, is mounted in front of the collimator slit. The bright H and K lines are easily visible in the spectrum of such an arc, although the same region of the solar spectrum is difficult to see distinctly. By means of a micrometer screw, the camera slit is made to coincide with one of the lines. Thus the only light which can reach the photographic plate is that of calcium vapor. Up to this time the mirror of the coelostat has been shielded from the Sun by a canvas screen, in order to protect it from distortion. After the photographic plate has been placed in position in its support in front of the camera slit, the canvas screen is removed and the solar image brought to a sharp focus on the collimator slit, by moving the concave mirror of the Snow telescope. The slide of the plate-holder is then drawn and the electric motor started. The screw, driven by the electric motor, then causes the entire spectroheliograph to move at a slow and uniform rate, so that the collimator slit passes over the solar image and the camera slit moves across the photographic plate.

If it is desired to take a photograph with a hydrogen line, instead of a calcium line, the prisms and mirror are adjusted until the line in question falls upon the camera slit, when the exposure is made as before.

In the daily programme of observations at least one photograph with the H_1 line of calcium, showing the faculae and low level calcium vapor; one with the H_2 line of calcium, showing the flocculi at a higher level; one with the $H\gamma$ line of hydrogen; and one with an iron line, are made in the early morning and again, if circumstances permit, in the late afternoon (Plates LXIII–LXVII). Since the weather is clear day after day through the summer and autumn months

(on 112 consecutive days in the summer of 1907), and not infrequently during the rainy season, the instrument thus yields a large number of plates, suitable for the comparative study of the flocculi.

Photographs of the prominences are also made daily, when circumstances permit. These are used to determine the changes in number and total area of the prominences during the Sun-spot period.

In the establishment of an observatory much remains to be done after successful photographs of astronomical phenomena have been obtained. Indeed, although the work of organization must be far advanced before photographs can be secured, the most important steps are still to be taken. For an astronomical photograph, while it may yield much new information from casual examination, is to be regarded as a document of great value, worthy of prolonged investigation. Every photograph of the Sun, for example, represents its changing phenomena as they were at the moment of the exposure, under conditions which will never be exactly repeated. The best methods of obtaining from photographs all the knowledge they are capable of conveying are to be arrived at only after the fullest consideration of the possibilities.

In chap. xi the most striking characteristics of the flocculi have been explained and illustrated. We must now consider how these objects may be systematically studied, in such a way as to contribute to our knowledge of the solar constitution. The most obvious peculiarity of the flocculi, apart from their change in form, is their motion across the Sun's disk. This is due to the solar rotation, which was first discovered through the daily motion of sun-spots. It is remarkable that the spots do not move as they would if they were fixed to the surface of a solid sphere. Spots in different latitudes move with different angular velocities, and

exhibit what is called the "equatorial acceleration;" i. e., spots near the Sun's equator complete a revolution in much shorter time than those in higher latitudes. At the equator the rotation period is about twenty-five days. At 10° north or south latitude the period is several hours longer, and at 45° it is about twenty-seven and a half days. The faculae, according to results obtained by Stratonoff and others, follow the same general law. Spectroscopic observations, based on an application of Doppler's principle show that the motion is not confined to the spots and faculae, but is also shared by the layer of metallic vapors (the "reversing layer") which lies just above the photosphere, and produces the dark lines of the solar spectrum by absorption of the white light coming through it from below. It thus becomes interesting to inquire whether the calcium flocculi, which we suppose to be clouds of luminous vapor lying at an elevation of several thousand miles above the photosphere, show a similar law of rotation.

The method employed to determine the rotation period of the spots is to measure their latitude and longitude, referred to the center of the Sun, on plates taken at intervals of one or more days, and in this way to ascertain the change of longitude of the same spot in twenty-four hours. By thus obtaining the velocities of spots in different latitudes the law of rotation can be derived. In considering the methods of measuring the latitude and longitude of a spot, we must remember that the plane of the Sun's rotation is inclined at an angle of about 7° with that of the Earth's orbit. The Earth passes through the nodes (the intersection of this plane with the ecliptic) about June 3 and December 5, and only on these dates do the spots appear to move in straight lines across the disk. The angle between the Sun's axis and the north and south line in the sky (called the "position angle" of the Sun's axis) varies about 53° in the course of

the year—about $26\frac{1}{2}°$ each side of zero. It is thus evident that in determining the latitude and longitude of a spot by ordinary methods of measurement considerable calculation will be required. The process employed at Greenwich, on the direct photographs of the Sun obtained there, is to measure the distance of the spot from the center, and the angle between the Sun's axis and the line joining the spot with the center of the disk. As the inclination of the Sun's axis is known for every day in the year, it then becomes possible to calculate the latitude and longitude of the spot.

This method is very satisfactory when a comparatively small number of objects are to be measured on each plate, which is the case with sun-spots. But the flocculi are so numerous, and offer so many points suitable for measurement, that the calculations required for each spectroheliograph plate would be very extensive. In seeking to find some simple method of abridging these calculations, it appeared that the solar photograph might be projected upon the surface of a globe ruled with meridians and parallels 1° apart. The axis of the globe being set at the inclination corresponding to the date of the photograph, it should then be possible to read off the latitude and longitude directly, by estimating the position, in tenths of a degree, of the flocculus in question, with reference to the nearest meridian and parallel (Plate LXIX). As the longitude of the center of the Sun's disk is tabulated for each day in the year, no calculations would be necessary, except to add or subtract this longitude in the case of each of the readings.

This method proved so satisfactory, when used at the Yerkes Observatory in measuring the Kenwood photographs, that it was afterward adopted, in perfected form, in the Computing Division of the Solar Observatory. The new globe-measuring machine, or "heliomicrometer," is illustrated in Plate LXX. Two 4-inch telescopes, shown in the

upper part of the cut, are pointed toward two plane silvered glass mirrors thirty feet away. One of these mirrors receives light from the spectroheliograph plate, which is mounted immediately under the right-hand telescope and illuminated by incandescent lamps from behind. The other receives light from a globe, mounted below the left-hand telescope and illuminated on its front surface. The images of globe and plate, given by the two telescopes, are brought together in a single eye-piece, so that the observer sees them superposed. If, then, the surface of the globe is ruled with meridians and parallels, as in the instrument previously described, the positions of the flocculi can be read off by estimation. However, it is desired in this case to attain a higher degree of precision in the measurements, and to see small and faint flocculi to better advantage than would be possible if they were observed in projection against the illuminated surface of the globe. Accordingly, a pair of cross-hairs, which can be moved over the plate in a horizontal or vertical direction by the observer at the eye-piece, is made to coincide with the object to be measured. The globe is then illuminated, and rotated in latitude and longitude until a point corresponding to the intersection of the equator and the central meridian falls exactly upon the cross-hairs. A circle, which can be read by the observer at the eye-piece, then shows the angle through which the globe has been turned in latitude. A second circle gives the distance in longitude from the center of the Sun. It is, of course, to be understood that the axis about which the globe is turned in measuring longitudes is set at the proper inclination for the date of the photograph. For less precise measurements, the position of the cross-hairs may be estimated with reference to the rulings on the (fixed) globe.

This instrument, which was constructed in the shop of the Solar Observatory, has proved very satisfactory in prac-

tice. It has been found that the latitudes and longitudes, thus read off directly, are as accurate as when determined by measuring the plate in an ordinary measuring-machine and performing the necessary calculations. Since the measurements can be be made quite as rapidly on the heliomicrometer as on the other machine, all the time required to make the calculations is saved. Thus one observer can measure a great number of flocculi, and the services of several computers are rendered unnecessary.

A discussion of the measurements made in this way shows that the flocculi follow a law of rotation similar to that which governs the spots and faculae. It will require some time to learn whether the velocities of the flocculi differ appreciably from those of the spots. It appears probable, however, from results thus far obtained, that the flocculi move with about the same velocity as the faculae. This would be a natural result, since, as already explained, the vapors of the flocculi probably rise from the faculae, and lie immediately above them.

The importance of providing for the closest possible correlation between all of the investigations of the Solar Observatory has already been mentioned. For this reason studies of the solar rotation should be made with reference to other solar work. The motions of individual flocculi frequently differ considerably from the average motions of the flocculi in the same latitude. Such differences, in many instances, are doubtless similar to those observed in the case of sun-spots, where they are related to the spot's activity, which varies greatly during the course of its development. However, the daily motion of a flocculus may also depend upon its height above the photosphere, and this may vary from day to day. It thus becomes desirable to learn whether differences in the height of flocculi can be detected and actually measured. For example, do the hydrogen flocculi lie at an average level

in the solar atmosphere above or below that of the calcium flocculi, and, if so, do they show differences of rotational velocity that may depend upon this fact?

It has already been explained, in chap. xi, that the calcium flocculi photographed when the bright H_2 or K_2 line is employed probably lie above the bright objects of similar form, but somewhat smaller area, which are photographed when the slit is set on the broad H_1 or K_1 band. It is not so obvious, however, that the average level of the hydrogen flocculi is above that of the H_2 and K_2 calcium flocculi, but this can be determined by accurate measurements. The forms of the dark hydrogen flocculi, as already remarked, closely resemble those of the bright calcium flocculi, though in many cases there are important differences (Plates LXXI and LXXII).[1] With the aid of the stereocomparator, an instrument manufactured by the Zeiss Optical Company for the purpose of making accurate comparisons of photographs, it is possible to observe a hydrogen photograph in superposition upon a calcium photograph, taken within so short an interval of time that no appreciable change occurred on the Sun between the exposures. With the monocular eye-piece of the instrument the two photographs, in precise superposition, are observed in quick succession. For this purpose a device is used which permits the eye to see one of the plates, and, immediately afterward, the other. If a micrometer wire is set on a calcium flocculus lying near the edge of the Sun, and the image of the corresponding hydrogen flocculus is then brought into view, it is found to be displaced slightly away from the center of the disk. This is not true of all the hydrogen flocculi. On the average, however, these dark hydrogen clouds seem to

[1] These photographs were separated by an interval of $2^h\ 26^m$, during which time the changes in the forms of the flocculi would not ordinarily be sufficiently marked to interfere with the general comparison of the more conspicuous features. In this case, however, the changes may have been rapid, since the numerous bright flocculi near the spot indicate great eruptive activity. For the accurate comparison of details, the photographs must be taken simultaneously.

be displaced in this way, by an amount representing a height of some 1,500 miles above the corresponding calcium clouds.[1] It will therefore be interesting to determine at some future time whether the rotational velocity of the hydrogen flocculi differs appreciably from that of the calcium flocculi.

An important step in the interpretation of spectroheliograph plates will be made when it can be ascertained whether anomalous dispersion plays any part in producing the phenomena recorded by them. Our present views as to the nature of Sun-spots, prominences, and other solar phenomena are based on the assumption that their light reaches us along nearly straight lines. If the pressure in the region through which the rays pass is low, this may be essentially true for white light. But we know that light of about the same wave-length as that of an absorption line in the spectrum, is bent far out of a straight path when it passes through the vapor to whose absorption the line is due. The consequences of this fact have led Julius to develop a new solar theory, based on the supposition that all metallic vapors at any given distance from the Sun's center are completely mixed, but not of uniform density throughout. Under these circumstances the chromosphere, prominences, and flocculi would not exist as we see them, but such appearances might be caused by anomalous dispersion of light passing out through the vapors from the interior of the Sun. A series of investigations, involving solar, stellar, and laboratory work, is being carried out on Mount Wilson for the purpose of testing this theory.

The rotation periods of sun-spots may depend upon their level, and this raises the old question as to the position of these objects with respect to the photosphere. According to the common view sun-spots are saucer-shaped cavities in the photosphere. This idea is based upon the observations

[1] This result must be checked on photographs taken simultaneously.

of Wilson, who found that when a spot is carried toward the limb by the solar rotation, the penumbra, on the side toward the center of the disk, is reduced in apparent width, as it would be, on account of its inclination to the line of vision, if it sloped downward toward the umbra. The best modern results do not offer any certain confirmation of this view, and thus render necessary an appeal to some independent test of the question. Ten years ago it was pointed out by Frost that the heat radiation of a spot, as compared with that of the neighboring photosphere, increases as the spot approaches the limb. From this it was naturally concluded that the spot must lie above the photosphere, at such a level as to escape the influence of the low-lying absorbing veil, which so greatly reduces the intensity of the photospheric light at the solar circumference. It has recently been found, however, that sun-spots radiate a much smaller proportion of violet light than the photosphere. As violet light is always reduced by an absorbing atmosphere in much larger proportion than light of longer wave-length, it follows that the observed effect would be seen in the case of sun-spots, even if they were at the same level as the photosphere. To remove the difficulty it is only necessary to confine the comparative measures to a single color, rather than to use the total radiation, comprising light of all wave-lengths.

The spectroheliograph affords a simple means of accomplishing this. It is employed to make photographs of a sun-spot and the surrounding photosphere on various dates, corresponding to the changing position of the spot on the solar disk. In making these photographs the camera slit is set, not on any of the spectral lines, but on a space between the lines, preferably in the yellow or red, since the influence of extraneous light will be least marked in this region. On account of the darkness of the spot, which would require an exposure about six times as long as that for the photosphere to give a

photograph of equal intensity, it is desirable to decrease the intensity of the photospheric light by a dark glass, placed over the slit, but so arranged as not to reduce the light from the sun-spot. In this way the spot and photospheric light can be compared from day to day, by means of photometric measurements. The same method can be employed to measure the level of the flocculi. Such work is now in progress at the Solar Observatory, in conjunction with the other investigations already mentioned. Since the level of a spot may affect its temperature, and therefore its spectrum, an attempt will be made to correlate this work, not only with determinations of the spot's motion, but also with the spectroscopic observations described in chap. xvii.

These few examples may suffice to give an idea of the character of the work done with the spectroheliograph of the Snow telescope. The vertical motion of the calcium vapor in the flocculi; the manner in which it flows horizontally over sun-spots; the relationship, in point of development, of flocculi to spots; and other similar matters, are also studied systematically. It may also be added that the area of the flocculi is measured on each day's plates, since it serves as an index to the Sun's activity, which may prove important when considered in its bearing on possible variations of the solar radiation and their effect on terrestrial phenomena.

CHAPTER XVII

A STUDY OF SUN-SPOTS

It has already been remarked (p. 69) that sun-spots, though apparently much darker than the photosphere, are, in reality, brilliantly luminous objects. Though they thus appear dark merely by contrast, the cause of their reduced brilliancy has given rise to much discussion. Some of the most recent theories have maintained that sun-spots are so much hotter than other parts of the solar surface that the photospheric clouds, due to condensation of the vapors rising from the Sun's interior, cannot form at these points. One of Lockyer's arguments in support of his hypothesis that the terrestrial elements are dissociated at the high temperature of the stars is based upon the view that at times of sun-spot maxima the spots are too hot to permit certain of the terrestrial elements to exist in them. This conclusion was founded upon a long series of observations of certain lines in the spectra of sun-spots. The spot spectrum differs from the solar spectrum in the fact that some of the solar lines are strengthened or widened, some are weakened, and many are unchanged (Plate LXXIV). The number of lines whose intensities are thus altered amounts to many hundreds; indeed, if the fainter lines are taken into account, to several thousands. Lockyer's observations consist in recording, on every clear day, the "twelve most widened lines" in the spectra of spots then visible on the Sun. His results seemed to indicate that at sun-spot minima the most widened lines represent known substances; while at sun-spot maxima many of these give place to unknown lines, which he attributed to unknown substances produced by dissociation of the

elements at the high temperature assumed to be characteristic of periods of greatest solar activity. Some of his later papers favor the view that sun-spots[1] possess a lower temperature than would thus be indicated, and he may therefore have decided to abandon the conclusions based on his earlier spectroscopic observations.

In spite of these results, and of all the theories which attribute high temperature to sun-spots, the more common opinion has been that they are regions of reduced temperature. This view has been based partly upon their decreased brightness, as compared with the photosphere, and partly upon the presence in their spectra of certain bands which, though unidentified, were supposed to represent molecules that cannot exist at the high temperature of the Sun. Accurate knowledge of these bands, however, was almost entirely lacking, on account of their faintness and the extreme difficulty of observing them visually.

It seemed probable that progress in this department of solar research might be expected to result from the successful application of photography to the study of spot spectra. Experiments made with this object in view at the Kenwood Observatory showed some of the principal widened lines, but failed to give the details needed for satisfactory work. These results were surpassed by photographs made by Young with the 23-inch Princeton refractor, but here also the need of more powerful instrumental means seemed to be apparent. The Kenwood experiments were continued with the 40-inch Yerkes telescope, and some of the "band lines," first observed visually by Maunder, were photographed, in addition to many of the widened lines. However, there was reason to believe that much better results could be obtained with the aid of a long-focus grating spectrograph, capable of photographing

[1] Because of the great strength of the titanium lines in *Arcturus*.

the spectrum on a large scale. Further work was therefore deferred until it could be taken up with the Snow telescope and a powerful Littrow or auto-collimating spectrograph.

This spectrograph is of a very simple type. The image of the Sun is formed on a slit, *s*, through which the light passes to a 6-inch collimating objective, *o*, of 18 feet focal length, which renders the rays parallel (Fig. 6). The rays then fall upon a plane grating, *g*, which diffracts them into a series of spectra. Light from a portion of one of these spectra returns to the objective, *o*, which forms an image of the spectrum on

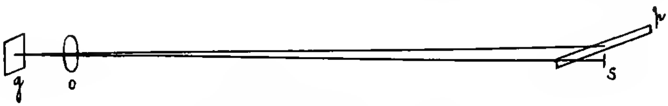


FIG. 6
Path of Rays in Littrow Spectrograph

a photographic plate, *p*, standing just above the slit. In order to form the image at this point the grating must be slightly inclined backward, so as to send the beam upward.

This instrument, as mounted for use with the Snow telescope, is shown in Plate LXXIII. As the tube of the spectrograph stands immediately above the spectroheliograph, a section of it can be rotated out of the way, to permit access to the prism-train of the latter instrument. When the spectrograph is to be used instead of the spectroheliograph, the concave telescope mirror is moved north through a sufficient distance to transfer the focal plane from the spectroheliograph slit to the spectrograph slit. Then, by inclining the mirror backward through a small angle, the solar image is raised to the proper height. After final focusing, a sun-spot is brought exactly upon the slit with the aid of slow-motion electric motors, connected with the concave mirror and controlled from a point near the focal plane.

In photographing the spectrum of a sun-spot, all light is

excluded from the spectrograph except that which comes from the umbra. This is done by covering all of the slit except a small portion at the center. The dispersion of the second or third order of the grating is usually employed. After this exposure has been completed, the center of the slit is covered and light from the photosphere admitted on each side. This gives a narrow photograph of the spot spectrum between two strips of solar spectra (Fig. 1, Plate LXXIV).

Casual examination of the spot spectra thus recorded is sufficient to show that the problem of interpreting them is not a simple one. If we consider, for example, the lines of some single element represented in the spot, we find that they are not all affected alike. Some are greatly strengthened, or perhaps attended by broad, faint wings. The former effect is so very pronounced, in certain cases, that lines wholly invisible in the solar spectrum are among the most conspicuous of the spot lines. Some of the solar lines, on the contrary, are greatly weakened, or entirely absent in the spot spectrum. Finally, there are many spot lines of unchanged intensity. Examples of most of these phenomena are illustrated in Plates LXXIV and LXXVI.

In order to interpret such results, it is necessary to have recourse to laboratory experiments. It might be supposed that the required knowledge of terrestrial spectra would be available in the literature of spectroscopy. This, however, is not the case. It is true that the lines in the spectra of most of the elements have been measured, and many experiments have been made on the changes in spectra produced by varying the conditions under which the vapors emit their radiations. It usually happens, however, when one attempts to apply published results to the interpretation of solar phenomena, that the data required for the solution of the particular problem in hand are lacking. Pressure, for example, is known to displace spectral lines toward the red,

and the actual shifts of certain lines of several different elements have been measured. But these form a very small percentage of the total number of lines in the spectra of these substances, and the shifts of any lines that happen to be under investigation are rarely found in the published tables. The same may be said of the effect of temperature on spectra. It has long been known that a reduction of temperature increases the relative brightness of certain lines, decreases that of others, and is without effect on the rest of the spectrum. Indeed, it was even known that some of the iron lines which are prominent at low temperatures are among the more conspicuous lines of spot spectra. But these instances were so few and scattered that no safe inferences could be based upon them. Moreover, it had not been definitely proved that these changes of relative intensity could actually be produced by temperature alone. Most of the experiments showing variations of spectra have involved the use of electric discharges, where causes are at work which might have a far greater influence than temperature change on the character of the spectra. Examples might easily be multiplied to show that the study of solar and stellar physics cannot be carried on effectively without a constant appeal to laboratory experiments, planned with special reference to the needs of the particular problem under investigation.

For this reason much stress has been laid in the equipment of the Solar Observatory upon the provision of suitable laboratory facilities. It seemed essential, in designing the spectroscopic laboratory on Mount Wilson, not only to include a considerable number of light-sources, which could be examined under various conditions of temperature, pressure, etc., but also to arrange them in such a way that the appeal to one or the other condition could be made without the delays ordinarily experienced when apparatus must be specially set up for a certain investigation. In the desired

plan the apparatus must be always ready, needing only the turning-on of an electric current, or the adjustment of a mirror, to bring it into action. It is not so much a question of the saving of time, which the provision of these means undoubtedly offers, as it is of the greatly increased efficiency of the working programme thus rendered possible. The immediate imitation in the laboratory, under experimental conditions subject to easy trial, of solar and stellar phenomena, not only tends to clear up obscure points, but prepares the way for the development along logical lines of the train of reasoning started by the astronomical work. Questions are constantly arising which, if partially or wholly answered by suitable laboratory experiments, may modify in an important way the daily programme of astronomical observations.

The arrangement of the apparatus in the spectroscopic laboratory of the Yerkes Observatory has already been described (p. 107). At the Solar Observatory an improved plan has been adopted. Instead of a circular wooden table, an annular concrete pier is employed, giving space on the inner wall for the various switches used to control the current supplied to the different sources, and also permitting the observer to inspect any light-source from the direction of the plane mirror at the center of the pier. Instead of a single plane mirror, two are provided, capable of rotating independently of one another about the same vertical axis. When the Littrow spectrograph is used to photograph the spectrum of any of the light-sources, only the lower plane mirror is in action. By setting this at the proper angle, light from any source on the annular pier can be sent to a concave mirror (seen near the middle of Plate LXXV), which forms an image on the slit of the Littrow spectrograph. If low dispersion, rather than high dispersion, is required, a one-prism quartz spectrograph is used. Again,

for the special study of certain lines under the highest resolving power, particularly in investigations of the Zeeman effect, an echelon spectroscope is used. In either case the concave mirror is tipped back at a small angle, so as to return the light to the upper plane mirror, from which it is reflected to the slit of one of these instruments. In Plate LXXV the quartz spectrograph may be seen just above the concave mirror, while the echelon spectroscope stands on the extreme right, near the end of the room. The Littrow spectrograph, which is ordinarily employed, is similar in type to the spectrograph used with the Snow telescope. The rectangular box which carries the slit and plate-holder of this instrument is shown on the pier in the lower left corner of Plate LXXV.

The following apparatus stands on the annular pier: the first instrument on the right is a powerful electro-magnet, used for the study of the Zeeman effect—i. e., the influence of a magnetic field in separating spectral lines into several components. For example, in the spectrum of a spark passing between iron terminals most of the lines appear single, even when observed with the great resolving power of an echelon spectroscope. If, however, the spark is placed between the poles of a powerful magnet, the effect of the magnetic field is to break each line up into several components. It would take us too far away from our immediate subject to discuss the theoretical questions which underlie these phenomena. It may be said, however, that by observing whether certain lines behave similarly under the influence of a magnetic field, we can tell whether they would be expected to act together in the Sun. It is not a question here of detecting magnetic phenomena in the Sun, since most careful study has not revealed any evidence of solar magnetic fields capable of affecting the appearance of the spectral lines. Nevertheless, the method provides an arbitrary means of picking out certain groups of lines, which may be so intimately related

to one another that we should expect them always to behave alike when observed in the Sun or stars.

In the illustration a mercury tube is suspended between the poles of the magnet and connected by heavy pressure tubing with a duplex vacuum pump, by which the pressure of the mercury vapor, illuminated by the discharge of an induction coil, can be reduced as desired. The current required for the magnet is supplied from a large storage battery in an adjoining building. This battery is the principal source of current for most of the apparatus on the annular pier; an alternating current, required for certain experiments, is obtained from a generator in the power-house.

It would be tedious to describe in detail all of the apparatus. It includes arrangements for studying the spark spectra of metals in air and in liquids; arc spectra in gases at high or low pressure; flame spectra, for which a Bunsen burner and an oxyhydrogen blow-pipe are required; vacuum tube spectra; etc. A small electric furnace permits the phenomena of anomalous dispersion to be observed in the vapors of sodium and other metals which melt at low temperatures. The auxiliary apparatus includes a special pump capable of compressing gases up to pressures of three thousand pounds to the square inch; an induction coil, giving a 16-inch spark; X-ray apparatus for the study of the effect of X-rays on the radiation of gases and vapors; a small heliostat, to supply sunlight; etc. All of the work on the solar image is done in the Snow telescope house, but sunlight is frequently required in the laboratory, to give a solar spectrum for comparison with the laboratory spectra.

Let us now return to the problem of explaining the strengthening and weakening of the solar lines in sun-spot spectra. As already remarked, there was reason to suspect that reduced temperature might be the effective cause of these changes. Accordingly, the spectrum of iron was

photographed by Gale and Adams in the electric arc, first with a large current (15 amperes), and then with a small current (2 amperes). It was found that most of the lines that are strengthened in spots are relatively strengthened in the 2-ampere arc, while most of the lines that are weakened in spots are also weakened in this arc. Furthermore, the majority of the lines showed no change of intensity, which is also the case with most of the iron lines in sun-spots. Similar results were obtained with titanium, vanadium, chromium, manganese, and other metals represented in spots.

The next question was to determine whether the metallic vapors in the 2-ampere arc are certainly cooler than in the 30-ampere arc. This is by no means an easy thing to decide, on account of various complicating elements that may not appear at first sight. However, it was a simple matter to compare the spectrum of the long flame which extends out from the arc with that of the core of the arc between the carbon poles. As the outer part of the flame is undoubtedly much cooler than the core of the arc, the effect of decreased temperature should be apparent here. The results confirmed, in the most complete manner, those obtained by reducing the current. In other words, in passing from the hot core of the arc to the cooler flame, changes in the relative intensities of the lines of the various metals, similar to those observed in comparing the solar spectrum with the sun-spot spectrum, were found. It thus seemed probable that the modified relative intensities of the lines in spots might be the result of a local reduction in temperature of the solar vapors.

However, it is not known precisely what part electrical phenomena in the arc may play in producing the characteristic radiations of the vapors. Indeed, opinions have differed so much on this subject that some of the ablest physicists ascribe the observed line intensities entirely to the electrical conditions of the arc, and do not admit that temperature

changes can have any influence upon them. Thus the results so far obtained would not be accepted as proof that the spot vapors are at a lower temperature than the corresponding vapors in the Sun's reversing layer. It remained to be seen whether simple reduction of temperature, under conditions which excluded any possible influence of electrical effects, would be competent to change the relative intensities of the lines in the same way as passage from the core to the flame of the arc had done.

The simplest way of testing this was to inclose the metal in question within a carbon or graphite tube (chosen because of its power to withstand very high temperatures), and to heat this tube by a powerful electric arc playing on its outer walls. Under these conditions, since the vapors are not observed within the electric arc, but are separated from the flame of the arc by the walls of the carbon tube, it should be possible to determine the effect of change of temperature on the relative intensities of the lines.

As the dynamo on Mount Wilson was not adequate to supply the electric power (50 kilowatts) desired for this work, the furnace was erected in the Pasadena laboratory of the Solar Observatory. As in an electric furnace used by Moissan, the arc was produced between two large carbon poles, in a box with carbon walls, surrounded by a large mass of magnesite, inclosed in a sheet-iron case. Running longitudinally through the carbon box, and between the poles of the arc, a carbon tube containing the metal was placed. This tube extended out through the walls of the furnace, so that light from the hot vapors seen through its open end could be focused on the slit of a Littrow spectrograph of 18 feet focal length (similar to the one used with the Snow telescope in photographing spot spectra).

With this furnace it did not prove to be possible to vaporize titanium and vanadium, but the test was made for

chromium and iron. The relative intensities of the lines of these metals were found to be very nearly the same as in the flame of the arc. In other words, the lines which are strengthened in passing from the core of the arc to the flame are also strengthened in passing from the core of the arc to the electric furnace. Moreover, even after the arc which heated the carbon tube in the furnace had been extinguished, the still glowing vapors continued to give a spectrum in which the lines strengthened in sun-spots were relatively strong.

But the proof is not yet complete. For, with the facilities available, it was not possible to vary the temperature in the furnace through a sufficient range to produce undoubted changes in the relative intensities of the lines. Therefore it might be argued that the increased intensity in the core of the arc of some lines, and the decreased intensity of others, are due to electrical phenomena, and not to increased temperature. The *inference* was strong that reduced temperature was the deciding factor in determining the relative intensities of the lines, since it is common to the flame of the arc and to the furnace, and since electrical effects were excluded in the latter. But the laboratory work cannot furnish an absolute *proof*, unless it should become possible, through increase in the temperature of the furnace, to produce spectra in which the relative intensities of the lines are the same as in the case of sun-spots. Experiments are now in progress with this end in view.

Fortunately, however, there are other sources of information to which we may appeal. In the reversing layer, oxygen exists in the presence of such substances as iron and titanium. Now, it is well known that this can be true only under conditions of very high temperature. Hence, if the metallic vapors in sun-spots are actually cooler than the vapors outside of spots, the reduction in temperature may be sufficient to permit the oxygen to enter into combination

with some of the metals present. Titanium oxide, in particular, is capable of resisting a very high temperature, which would immediately dissociate an oxide of iron. Is there any evidence, then, that titanium oxide exists in sun-spots?

Thanks to the excellent photographs of spot spectra obtained with the aid of the Snow telescope, this question is easily answered. Titanium oxide gives a very characteristic *fluted* spectrum, consisting of bands in which the numerous lines lie closer and closer together until they terminate in definite "heads." Fig. 2, Plate LXXIV, shows some of these titanium oxide flutings in the extreme red end of the spectrum, as photographed (on specially sensitized plates) in the outer flame of the electric arc. The photograph is a *negative;* i. e., the lines which are bright in the arc are shown dark, to facilitate comparison with the dark lines in the photograph of the spot spectrum, shown just above the titanium oxide spectrum. It will be seen at a glance that each of the heads of the fluting is represented in the spot, and that a great number of the fine lines which make up the fluting also agree in position with corresponding spot lines. The spot spectrum contains many lines not represented in the arc, which are due to substances other than titanium oxide. The arc spectrum also contains a few lines due to impurities, which are not present in the spot. Nevertheless, the general agreement is so perfect that the presence of the titanium oxide bands in spot spectra cannot be doubted. Several other bands belonging to the same substance are also represented in our photographs of spot spectra.

The identification of these bands by Adams would seem to leave no doubt as to the reduced temperature of the spot vapors. The objection might be made, it is true, that some question exists as to whether these bands are actually due to the oxide, since there is some reason to suppose that titanium

itself is capable of producing them. However, the molecule which gives them rise undoubtedly differs from the atom which produces the line spectrum of titanium. In laboratory experiments the flutings become more and more conspicuous as the temperature is reduced, suggesting that the molecule is broken up at high temperatures. The absence of the flutings from the spectrum of the Sun sustains this inference. Moreover, Fowler, in London, has since found some of the green flutings in the Mount Wilson photographic map of the spot spectrum to be due to magnesium hydride, and Olmsted, on Mount Wilson, has identified some of the red flutings with those of calcium hydride.

It therefore appears to be true that the vapors which constitute the umbra of a sun-spot are cooler than the corresponding vapors in other parts of the Sun. This would readily account for the relative intensities of the spectral lines and for the comparative darkness of sun-spots. But the cause of such a reduction of temperature is yet to be determined. Knowledge of the comparatively low temperature of spot vapors at once permits us, however, to discard various spot theories which postulate very high temperatures, and to attack the question of the true meaning of sun-spots in an intelligent manner.

In order to facilitate the spectroscopic study of sun-spots, a preliminary photographic map of the spot spectrum has been issued by the Solar Observatory. This consists of twenty-six sections, each covering one hundred Ångström units of the spectrum, the whole map extending from wave-length 4600 to wave-length 7200. In enlarging the original negatives, Ellerman photographed each section on a sensitive plate, moved up and down (in the direction of the spectral lines) during the exposure. This process widened the narrow spot spectrum, and rendered visible many slight changes in the relative intensities of lines which would otherwise escape

notice. Beside each strip of the spot spectrum the normal solar spectrum is given for comparison (Plate LXXVI).

The information derived, as explained above, from solar and laboratory investigations applies not only to the Sun. If, by cooling in some degree the vapors lying within a limited area on the solar surface, the spectrum is changed in the manner illustrated in sun-spots, it should follow that if the entire Sun, or a star like the Sun, were cooled in the same degree, its spectrum would resemble that of a sun-spot. Our ideas of stellar evolution are based on the belief that stars exist in all stages of development and differing greatly in temperature. If our inference be correct, we should find, among the stars which have passed by continued cooling beyond the solar stage, some in whose spectra spot lines appear. The next chapter explains how this test has been applied.

CHAPTER XVIII

STELLAR TEMPERATURES

THE advantages of great resolving power in spectroscopic work have been mentioned in previous chapters. In the case of the Sun the amount of light at our disposal is so abundant that grating spectroscopes of very high dispersion can be used without difficulty. The degree in which the light is weakened by dispersion will be appreciated when it is remembered that the light entering the spectroscope through a slit one-thousandth of an inch in width is spread out into a spectrum many feet in length. In the case of the stars, however, only a small amount of light is at our disposal, and for this reason the spectroscopes employed have always been much inferior in dispersion to those used for solar research. The interpretation of stellar spectra is thus rendered difficult, since several closely adjacent lines may be compressed into one. If, then, we are to learn the true relative intensities of stellar lines, in order, for example, to make certain of any apparent analogy with sun-spots, we must find means of studying stellar spectra with a dispersion as great as that used for solar observations.

A difficulty which does not exist in visual observations has an important bearing on the nature of the spectroscopes required for such work. If it were possible to *see* the spectrum of a star to good advantage, a high resolving power could be obtained with a spectroscope of moderate dimensions, supplied with a powerful grating. But, for two principal reasons, photographic methods are almost exclusively used in stellar spectroscopy. In the first place, except in the case of a few of the brightest stars, the smaller details of stellar

spectra cannot be seen, on account of the faintness of the light. In the second place, the unsteadiness of the image, due to atmospheric disturbances, causes the extremely narrow spectrum to flicker so seriously as to prevent any refined work. This flickering, however, has no effect upon the photographic plate, which merely sums up all of the light it receives during the exposure. Moreover, by prolonging the exposure, a spectrum too faint to be seen can be recorded photographically. In all modern work of precision, therefore, photographs of stellar spectra are substituted for visual observations.

But the photographic plate has a granular structure, due to the fact that it is made up of silver grains, which can be separately distinguished with a microscope. On account of this granular structure of the plate the details of the image are imperfectly recorded, so that no advantage results from the use of high powers when examining the plate. If the visual image could be well seen at the spectroscope, an increase of magnification (attained by the use of a suitable eye-piece) would separate all lines within the resolving power of the prisms or grating. On the photographic plate, however, the images of these lines may lie so close together that they appear as one, and cannot be separated by magnification. What is needed, in order to realize photographically the full resolving power of the prisms or grating employed, is a spectroscope of such length that the closest lines that could be distinguished visually are so far separated as to be independently recorded, in spite of the effect of the silver grains.

The powerful grating spectrograph used by Rowland in his study of the solar spectrum has a focal length of 21 feet. Photographs made with a spectrograph of this size show nearly all the lines that can be separately distinguished in visual observations with the same instrument. Obviously it would be out of the question to attach such a spectrograph,

or even an equally powerful one of the more compact Littrow type, to the end of a movable telescope tube. Moreover, the very high dispersion would demand, in the case of stars, exposures prolonged for many nights. Temperature changes, or the slightest flexure of the apparatus during the exposure, would shift the position of the lines on the plate and thus destroy, by producing a blurred image, all the advantages afforded by large spectrographs.

Such instruments as the three-prism spectrograph of the Potsdam Astrophysical Observatory, the Mills spectrograph of the Lick Observatory, and the Bruce spectrograph of the Yerkes Observatory, give beautifully defined photographs of stellar spectra, from the measurement of which the motions of stars in the line of sight are determined with great precision. For most classes of work such spectrographs could hardly be surpassed. Nevertheless, the necessary limitations of resolving power and focal length in these instruments prevents them from separating many of the lines resolved by Rowland in his studies of the solar spectrum. It is evidently to be greatly desired that the spectra of a few of the brightest stars, at least, be photographed with spectrographs as powerful as Rowland's. In order to accomplish this the spectrograph must be fixed in position on a massive pier, and maintained at a constant temperature throughout the exposure.

To test the feasibility of this, and to decide whether a spectrograph of high dispersion could advantageously be used with a 60-inch reflecting telescope (p. 228), a grating spectrograph of 13 feet focal length has been tried with the Snow telescope. This instrument was mounted on the triangular stone pier (p. 133, Fig. 5) in the spectroscope house of the Snow telescope. The pier is inclosed in a room so constructed that the fluctuations of temperature within it are very slight. The 6-inch Rowland plane grating was mounted so as to form the front wall of a cubical metallic

box containing water. An extremely delicate thermostat, consisting of a bulb containing saturated ether vapor immersed in the water, caused a column of mecury to make or break an electric circuit if the temperature of the water varied as much as a hundredth of a degree. When the temperature fell by this amount, a relay turned on the current of two incandescent lamps immersed in the liquid. The heating produced by the lamps raised the temperature, and the current was then automatically cut off. The water was constantly stirred by small propellers driven by an electric motor. In this way the grating, which is, of course, the most sensitive part of the apparatus, was kept at an almost perfectly constant temperature throughout the exposure.

Arcturus, on account of its yellowish color and the character of its spectrum, has long been considered to represent a stage of stellar development somewhat advanced beyond that of the Sun. As its spectral lines show its chemical composition to be practically the same as that of the Sun, a reduction in temperature, due to cooling continued beyond the solar stage, should, on the hypothesis developed in the last chapter, cause its spectrum to resemble that of a sunspot. Accordingly, the spectrum of *Arcturus* was photographed with the Snow telescope and the grating spectrograph.

Because of the great dispersion, an exposure of five hours, which was all that could be given on a single night, was entirely insufficient. In fact, an exposure continued for five nights in succession, and aggregating twenty-three hours, was required. During all this time it was essential that the temperature of the grating remain practically constant, and that none of the parts of the spectrograph be displaced by any cause. For this reason the observer did not enter the constant-temperature room after the exposure was started, but merely brought the star to the slit of the spectrograph

each night, and maintained it there, by watching the star image reflected from the slit jaws, and correcting any slight deviations in its position. The same process was repeated from night to night, until the exposure was completed.

In these first experiments the possibilities of the method were not fairly tested, on account of some imperfections in the apparatus. The Snow telescope was designed for solar work, and is not well adapted for stellar observations. Moreover, work in progress on the telescope house caused some vibration of the piers, which doubtless affected the definition. Nevertheless, the resulting photographs are sufficiently good to show that this method, when properly carried out with the 60-inch reflector, should give a few stellar spectra not essentially inferior to the best obtained in solar work. The 60-inch reflector will collect about six times as much light as the Snow telescope, and the exposure time, for the same dispersion, will be decreased in about this ratio. Thus the spectrum of *Arcturus* should be photographed with the grating used for the present work in about four hours. As subsequent experiments with the Snow telescope showed that large prisms can be used to much better advantage than the grating for stellar spectra, this exposure time, for the same dispersion, will be still further reduced. In the case of the 60-inch reflector, the dispersion will be increased sufficiently to make the scale of the spectrum about the same as that of Rowland's solar spectrum photographs.

Plate LXXVII shows a portion of the *Arcturus* spectrum thus photographed, in comparison with spot and solar spectra. Barring some exceptions, which require further study, it will be noticed that the spectrum resembles the spot spectrum more closely than it does the solar spectrum.[1] On account

[1] In comparing these spectra, changes of intensity should be noted with refer nce to adjoining (unaffected) lines *in the same spectrum.* Unavoidable differences of absolute intensity in the photographs prevent a satisfactory comparison, unless this precaution be observed.

of the imperfections of the *Arcturus* photograph, many of the lines are shown with less contrast than they would ex-exhibit in a really good negative. However, the illustration should be sufficient to indicate the important bearing of spot spectra on the question of stellar temperatures.

The earliest classification of stellar spectra was that of Secchi, who distinguished four principal types: I, spectra of white and bluish-white stars, like *Sirius*, which contain broad and strong hydrogen and calcium lines, and but few lines, narrow and comparatively faint, of other elements; II, spectra of yellowish-white stars, like the Sun; III, spectra of red stars, containing a very characteristic series of bands, not identified by Secchi; IV, spectra of another class of red stars, containing the strongly marked bands of carbon. The bands in the spectra of stars of Secchi's third type were finally identified by Fowler, who showed that they are due to titanium oxide. In view of the presence of these same bands in spot spectra (Fig. 2, Plate LXXIV), it becomes interesting to inquire whether the lines in stellar spectra of this type also resemble those in sun-spots.

The brilliant red star *Betelgeuze* (*a Orionis*) which presents so striking a contrast with the bluish star *Rigel*, in the constellation of *Orion*, is a good representative of the third type. It was accordingly selected to test the question. A dense flint glass prism belonging to the 5-foot spectroheliograph was substituted for the grating in the large stellar spectrograph of the Snow telescope, and the thermostat was modified so as to control the temperature of the air surrounding the prism. In this way the spectrum of *a Orionis* was photographed by Adams, with a total exposure of seven hours on two consecutive nights. The work was done during the rainy season, and clouds, followed by continuous bad weather, cut short the exposure on the second night, and prevented the observations from being continued. The plate, while not

strong enough to be of the best quality, is nevertheless sufficiently good to serve for the purpose of a general comparison. It was found that essentially all of the lines are stronger than in the Sun, and that lines which are strengthened in spots are much more decidedly strengthened in *a Orionis* than lines unaffected in spots. In fact, the relative strengthening is much more marked in the case of this star than in the spots themselves, probably indicating that its temperature is lower. As the titanium oxide flutings form a conspicuous feature of the spectrum of *a Orionis*, and are also present in sun-spots, the evidence appears to be practically complete. More detailed investigations will undoubtedly reveal various discrepancies, due to differences in chemical composition or physical condition. Nevertheless, it may be said, in general, that the resemblance between the spectra of sun-spots and those of third-type stars is so close as to indicate that the same cause is controlling the relative intensities of many lines in both instances. This cause, as the laboratory work indicates, is to be regarded as reduced temperature.

Thus we have been led, through the study of certain phenomena of our typical star, the Sun, and through their interpretation by laboratory experiments, to the consideration of the general question of stellar temperatures. Let us now inquire whether other independent methods can be applied to determine these temperatures, dealing first with the possibility of measuring directly the heat radiation of stars.

The early experiments of Huggins and Stone failed, for lack of suitable apparatus, to detect the exceedingly small degrees of heat which reach us from stellar sources. Even Boys was no more successful in 1888, though he concentrated the stellar radiations on his newly invented radiomicrometer, which would show $\frac{1}{1000000}$ of a degree rise of temperature. With the sensitiveness used, $\frac{1}{150000}$ of the

heat received by his telescope mirror from the full Moon could be detected. Yet the brightest stars produced no certain effect. As the result of this work, Boys was convinced that no star sends us as much heat as would be received from a candle at a distance of 1.7 miles, if there were no atmospheric absorption.

The subject of stellar heat was investigated by E. F. Nichols at the Yerkes Observatory, in 1898 and 1900. The radiometer employed as the heat-measuring apparatus consisted of two circular vanes of mica, each about one-twelfth of an inch in diameter, attached to the opposite ends of a delicate cross-arm of drawn glass, cemented to a whip of fine drawn glass about one and one-quarter inches long. To the lower end of this system a minute mirror, made by silvering a fragment of very thin microscope cover-glass, was attached, and the whole was suspended by a very fine quartz fiber in a vacuum chamber. This radiometer was mounted on a pier in the coelostat room of the Yerkes Observatory. A coelostat reflected the starlight to a 24-inch mirror of 8 feet focal length, which concentrated the stellar rays upon one of the vanes, after entering the radiometer case through a window of fluorite, which is very transparent to heat radiations. By observing a scale reflected in the small mirror attached to the radiometer suspension, the deflection of the vane, which indicated the heating effect of the stellar rays, could be measured. In this way it was found that *Arcturus* sends us about as much heat as would be received from a candle six miles away, if there were no absorption in the atmosphere. *Vega* has less than half the thermal intensity of *Arcturus*.

The extraordinary sensitiveness of the apparatus employed may be illustrated by some observations of a candle 2,500 feet from the observatory. Heat from this candle, when concentrated on the radiometer vane of the 24-inch mirror, gave a deflection of about sixty-two scale divisions. On one

occasion the assistant extinguished the candle and placed his head in front of it when the signal was given, instead of uncovering the flame. The deflection caused by the heat radiation of his face, at a distance of 2,500 feet, was twenty-five scale divisions! With no atmospheric absorption, the number of candles in a group at a distance of sixteen miles could be determined from the average of a series of measurements of their total heat radiation.

As *Arcturus* and *Vega* appear about equally bright to the eye, the greater heat radiation of the former star indicates that it sends out a larger proportion of the long (red) waves. If neither star possessed an absorbing atmosphere, it might then be concluded that *Arcturus* is cooler than *Vega*, but so much larger in angular diameter, when seen from the Earth, as to be fully as bright as *Vega*, and to send us more than twice as much heat. However, since we know that the absorbing atmosphere of stars like *Arcturus* is much denser than that of stars like *Vega*, this conclusion would not hold. We are therefore not in a position to judge from these experiments as to the relative temperatures of these stars.

Lockyer has recently endeavored to determine the relative temperatures of stars by comparing their spectra, when photographed under similar conditions, in order to learn which of two stars sends us the greater proportion of violet light. In accordance with a well-known law, the proportion of violet light emitted by a luminous body increases as the temperature rises. By measuring the position of maximum intensity in the spectrum of a star, it should thus be possible to determine its temperature. Unfortunately, however, as already remarked, no absolutely safe conclusions can be based upon a test of this kind. Stars with dense atmospheres must appear red in color, no matter what their temperature, as compared with stars whose atmospheres are much less dense. For

we have here just such a condition of things as we observe in the setting Sun, which appears red simply because the violet rays are more highly absorbed by our atmosphere than the red rays. It seems to be true that the older and cooler stars have denser atmospheres than the younger and hotter ones. It is thus probable that the stars whose spectra contain the greater proportion of red light actually are cooler than those in which the violet light is relatively stronger. But the fact remains that we are not warranted in basing determinations of stellar temperatures on measurements which so obviously depend upon the effect of atmospheres of unknown density. We will return to this question of stellar temperatures in a further consideration of the classification of stars (chap. xx).

CHAPTER XIX

THE NEBULAR HYPOTHESIS

In the preceding chapters we have seen how the study of stellar evolution depends primarily upon the most accurate knowledge we can obtain of the Sun, regarded as a typical star. We have also examined certain methods of observing solar, stellar and laboratory phenomena, and have taken advantage of the opportunity afforded by the peculiarities of Sun-spot spectra to illustrate the mutual dependence of these various means of research. In passing to certain of the more general considerations underlying our subject, we may now examine some of the principal hypotheses which have been offered to account for the development of solar and stellar systems.

Passing over the important speculations of Kant, and the conclusions drawn by Herschel from his extensive observations, we reach the nebular hypothesis of Laplace. This celebrated explanation of the origin of the solar system has dominated the world's thought since the very date of its publication. The eminence of its author, and the unique value of his great work on celestial mechanics, led to the immediate acceptance of his ideas, even when advanced in speculative form and without the support of mathematical analysis. The greatest physicists and astronomers of the nineteenth century have given the weight of their approval to the nebular hypothesis, and all calculations as to the age of the Sun have been based upon it. When viewing it in the light of recent destructive criticism, we must not forget the value of Laplace's speculations in directing thought and in seeking to account, by a single generalization, for a host of

observed phenomena. Nor must we overlook his remark that the hypothesis was presented "with the distrust which should be inspired by everything that is not the result of observation or calculation." The widespread and favorable influence exerted by the hypothesis on the intellectual life of the nineteenth century cannot be destroyed by recent developments. In the same way, the beneficial effect of Darwin's work on organic evolution would remain, even if the hypothesis of natural selection were forced from its place by that of mutation.

As the original statement of the nebular hypothesis is not easily accessible to every reader, it seems desirable to include here a free translation of Note VII, at the end of Laplace's *Exposition du système du monde*. A few paragraphs, dealing with more technical details, are omitted, but all of the essential features are retained.

In seeking to trace the cause of the original motions of the planetary systems, the following five phenomena, enumerated in the last chapter (of Laplace's book), are available: the motions of the planets in the same direction and nearly in the same plane; the motions of the satellites in the same direction as the planets; the motions of rotation of these different bodies and of the Sun in the same direction as their orbital motions, and in but slightly different planes; the small eccentricity of the orbits of planets and satellites; finally, the great eccentricity of comets' orbits, as though their inclination had been left to chance.

So far as I am aware, Buffon is the only one who has endeavored, since the discovery of the true system of the world, to trace the origin of the planets and their satellites. He supposes that a comet, falling upon the Sun, drove from it a torrent of matter, which reunited at a distance in several globes, varying in size and in distance from the Sun; these globes, having become opaque and solid by cooling, are the planets and their satellites.

Laplace then goes on to show that, although this hypothesis might account for the first of the five phenomena

mentioned above, the others could not be explained by it. In seeking to discern their true cause, he continues as follows:

Whatever be its nature, since it has produced or directed the motions of the planets, it must have embraced all of these bodies, and, in view of the prodigious distances that separate them, it could only have been a fluid of immense extent. In order to give them a nearly circular motion about the Sun, in the same direction, the fluid must have surrounded this body like an atmosphere. The consideration of planetary motions thus leads us to think that, as the result of excessive heat, the solar system originally extended beyond the orbits of all the planets, and that it contracted by successive steps to its present limits.

In the assumed primitive condition of the Sun, it resembled those nebulae which are shown by the telescope to be composed of a more or less brilliant nucleus, surrounded by nebulosity which, in condensing toward the surface of the nucleus, transforms it into a star. If, by analogy, we conceive of all the stars being formed in this manner, we may imagine their earlier nebular state, itself preceded by other states, in which the nebular matter was more and more diffuse, the nucleus being less and less luminous. By going back as far as possible, we thus arrive at a nebulosity so diffuse that its existence could hardly be suspected.

Philosophical observers have long been impressed with the peculiar distribution of certain stars visible to the naked eye. Mitchel has remarked on the improbability that the stars of the *Pleiades*, for example, could have been compressed within the narrow limits which inclose them by mere chance, and he has hence concluded that this group of stars, and similar groups in the heavens, are the effects of an original cause or of a general law of nature. These groups are the necessary result of the condensation of nebulae having several nuclei; for it is evident that, if the nebular matter were continually attracted by these various nuclei, they would ultimately form a group of stars like that of the *Pleiades*. The condensation of nebulae having two nuclei will similarly form stars lying very close together, and revolving about one another, like the double stars whose motions have already been observed.

But how has the solar atmosphere determined the motions of rotation and of revolution of the planets and satellites? If these

bodies had penetrated deeply into this atmosphere, its resistance would have caused them to fall upon the Sun. We may thus conjecture that the planets were formed at its successive limits, by the condensation of zones of vapors which the Sun, in cooling, must have abandoned in the plane of its equator.

Let us recall the results given in a preceding chapter. The atmosphere of the Sun could not have extended out indefinitely. Its limit was the point where the centrifugal force, due to its motion of rotation, balanced the attraction of gravitation. Now, as cooling contracted the atmosphere and condensed at the surface of the Sun the molecules lying near it, the motion of rotation accelerated. For, from the law of areas, the sum of the areas described by the radius vector of each molecule of the Sun and of its atmosphere, when projected on the plane of its equator, being always the same, the rotation must be more rapid when these molecules approach the center of the Sun. The centrifugal force due to this motion thus becoming greater, the point where it equals the weight is nearer the Sun. If we then adopt the natural supposition that the atmosphere extended, at some period, to an extreme limit, it must have left behind, in cooling, the molecules situated at this limit and at the successive limits produced by the acceleration of the Sun's rotation. These abandoned molecules must have continued to revolve around the Sun, since their centrifugal force was balanced by their weight. But since this equilibrium did not obtain in the case of the atmospheric molecules in higher latitudes, their weight caused them to approach the atmosphere as it condensed, and they did not cease to belong to it until this motion brought them to the equator.

Let us now consider the zones of vapor successively left behind. To all appearances these zones should form, by their condensation and the mutual attraction of their molecules, various concentric rings of vapor revolving around the Sun. The mutual friction of the molecules of each ring should have accelerated some and retarded others, until they had all acquired the same angular velocity. Thus the linear velocities of the molecules farthest from the center of the Sun must have been the greatest. The following cause would also contribute toward the production of this difference of velocity. The molecules farthest from the Sun, which, through the effects of cooling and condensation, came together to form the outer part of the ring, always described areas proportional to the

time, since the central force which controlled them was constantly directed toward the Sun. This constancy of areas requires that the velocity increase as the molecules move inward. It is evident that the same cause must have diminished the velocity of those molecules which moved outward to form the inner edge of the ring.

If all the molecules of a ring of vapor continued to condense without separating, they would finally form a liquid or solid ring. But the uniformity which this formation demands in all parts of the ring, and in their rate of cooling, must have rendered this phenomenon extremely rare. Thus the solar system offers only a single example of it, that of the rings of *Saturn*. In almost all cases each ring of vapor must have broken into several masses which, having only slightly different velocities, continued to revolve at the same distance around the Sun. These masses must have assumed a spheroidal form, with a motion of rotation corresponding in direction with that of their revolution, since their inner molecules had smaller linear velocities than their outer molecules; they thus formed as many planets in a vaporous state. But if one of them had possessed sufficient power of attraction to bring all the others successively together about its own center, the vaporous ring would thus have been transformed into a single spheroidal mass of vapor, revolving about the Sun and rotating in a direction corresponding to that of its revolution. This latter case has been the most common one. Nevertheless, the solar system offers an example of the first case in the four minor planets which lie between *Jupiter* and *Mars*; unless we suppose, in agreement with M. Olbers, that they originally formed a single planet broken up by a violent explosion into several parts having different velocities.

Now, if we follow the changes which ultimate cooling must have produced in the vaporous planets whose formation we have just pictured, we shall witness the production, at the center of each, of a nucleus which continues to develop through the condensation of the atmosphere surrounding it. In this state the planet exactly resembles the Sun in its primitive nebular condition. Cooling must thus have produced, at the various limits of its atmosphere, phenomena similar to those we have described; that is to say, rings and satellites revolving around its center in the direction of its motion of rotation, and turning in the same direction upon themselves. The symmetrical distribution of *Saturn's* rings about its center and in the plane of its equator naturally results from this

hypothesis, and would be inexplicable without it. These rings seem to me ever-present proofs of the original extension of *Saturn's* atmosphere and of its successive retreats. Thus the singular phenomena of the slight eccentricity of the orbits of the planets and satellites, the small inclination of these orbits to the solar equator, the identity in direction of the motions of rotation and revolution of all these bodies with that of the solar rotation: flow from our hypothesis and give it great probability.

If the solar system had been formed with perfect regularity, the orbits of the bodies which compose it would have been circles whose planes, like those of the various equators and rings, would have coincided with the plane of the solar equator. But it may be conceived that the endless varieties which must have existed in the temperature and density of the various parts of these great masses produced the eccentricity of their orbits and the deviation of their motions from the plane of this equator.

In our hypothesis, comets are strangers to the planetary system. In considering them, as we have done, to be small nebulae wandering from system to system, and formed by the condensation of nebular matter distributed with such profusion throughout the universe, we perceive that, when they arrive in the region of space where the solar attraction is predominant, it forces them to describe elliptical and hyperbolic orbits. But their motions being equally possible in all directions, they must move indifferently in all directions and at all inclinations to the ecliptic; which is in agreement with observation. Thus the condensation of nebular matter. by which we have just explained the motions of rotation and revolution of the planets and satellites in the same direction, and in planes differing but slightly, also explains why the motions of comets do not agree with this general law.

Laplace, after discussing the great eccentricity of comets' orbits, as bearing on the nebular hypothesis, continues as follows:

If certain comets entered the atmospheres of the Sun and planets during the formative period they must have fallen upon these bodies, after pursuing spiral paths. The result of their fall would be to cause the planes of the orbits and the equators of the planets to deviate from the solar equator.

If in the zones left behind by the solar atmosphere there were molecules too volatile to combine among themselves or with the planets, they must have continued to revolve about the Sun. They would thus give rise to such an appearance as that of the zodiacal light, without offering appreciable resistance to the various bodies of the planetary system, either because of their extreme rarity, or because their motion is very nearly the same as that of the planets which they encounter.

A close examination of all the details of the solar system adds still further to the probability of our hypothesis. The original fluidity of the planets is clearly indicated by the flattening of their figure, in conformity with the laws of mutual attraction of their molecules; furthermore, it is proved in the case of the Earth by the regular diminution of weight from the equator to the poles. This condition of original fluidity, to which we are led by astronomical phenomena, should show itself in the phenomena of natural history. But, to perceive it there, it is necessary to take into account the immense variety of combinations formed by all terrestrial substances mingled together in a state of vapor, when the reduction of temperature permitted their elements to unite among themselves. It is also necessary to consider the enormous changes that this fall of temperature must have brought about successively within the Earth and upon its surface, in all formations, in the constitution and the pressure of the atmosphere, in the ocean, and in the bodies which it held in solution. Finally, consideration should be given to violent disturbances, such as great volcanic eruptions, which must have modified, at various epochs, the regularity of these changes. Geology studied from this point of view, which unites it to astronomy, will acquire precision and certainty in many particulars.

Although the nebular hypothesis received almost universal acceptance, objections and difficulties were brought forward at various times during the nineteenth century. The criticisms of Babinet and Kirkwood were followed by the arguments of Faye, who concluded that the planets, if developed from the ring-system of Laplace, should rotate in the opposite direction. Laplace had assumed that the rings which were to form the planets revolved like solid bodies, their

outer edge traveling faster than the inner one. This would have involved forward rotation of the planets, as now observed. But such a condition of things could not have occurred—the rings, split asunder by the forces acting upon them, must have followed Kepler's laws, which would require the inner edge to move the faster. The rings of *Saturn*, held up by Laplace as a striking illustration of his views, were shown by Maxwell in 1859 to be composed of small bodies like meteorites. This was the result of a mathematical demonstration that the rings, if solid, would fly to pieces. It was confirmed by Keeler, in 1895, by one of the most beautiful applications of the spectroscope ever made. According to Doppler's principle, the position of a line in the spectrum of a moving body depends upon the velocity of the motion. This is true, even when the light is reflected from the surface of the moving body, after being received from the Sun. If the inner edge of *Saturn's* ring is moving faster than the outer edge, the lines in the spectrum of the ring should be increasingly bent toward the violet (on the approaching side of the planet) or toward the red (on the receding side), in passing from the outer toward the inner edge. Keeler's photograph of *Saturn's* spectrum shows this to be the case. Thus we have certain proof that *Saturn's* rings are made up of meteorites, each moving at the velocity a satellite would have at the same distance from the planet.

In spite of these and kindred objections, the nebular hypothesis, at least in its general outlines, retained its commanding position until subjected to a searching test instituted by Chamberlin and Moulton. The principal arguments brought together in Moulton's paper, entitled "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics,"[1] and in the discussion of the question in Volume

[1] *Astrophysical Journal*, Vol. XI (1900), p. 103.

II of Chamberlin and Salisbury's *Geology*, are briefly summarized below.

In the paper just referred to, Moulton defines the nebular hypothesis in much more general terms than Laplace employed. In other words, in order to make the test as complete as possible, he assumes that the original nebula might consist of a gas or of a swarm of meteorites, since Darwin had proved mathematically that the properties of gases may be fulfilled in a meteoroidal swarm. Moulton's discussion, moreover, does not insist upon the assumption of a very high temperature, since the progress of knowledge has shown that the present heat of the Sun may be accounted for as a result of the contraction of a nebula originally at a low temperature. Finally, the breaking-up of the nebula is not limited to the abandonment of rings, but is considered to include possible division by some fission process, the separated portions having contracted to form the planets and satellites.

The fact that the revolutions of certain satellites, such as those of *Uranus* and *Neptune*, are in a retrograde direction, while the planes of the orbits of the four satellites of *Uranus* are almost perpendicular to the plane of the planet's orbit, is an old argument against the nebular hypothesis. While the former difficulty could easily be overcome, the great inclination of the orbits of these satellites and that of *Neptune* seems to be directly opposed to Laplace's views. In the second place, the masses of the various planets, as well as the densities of the rings from which they are supposed to be formed, are shown to be entirely out of harmony with what the hypothesis would lead us to expect. Again, the inner satellite revolves about *Mars* in a period less than a third of the planet's rotation, while the hypothesis would require its velocity to be much less than that of the planet's surface. Darwin has shown that the friction of solar tides might have

retarded the rotation of *Mars*, without affecting the satellite's motion. But Moulton points out that the inner edge of *Saturn's* ring completes a revolution in about half the time of *Saturn's* rotation period. At this great distance from the Sun, the very small tides could not have retarded sufficiently the rotation period of *Saturn*, unless they have been operating several thousand times as long as the Martian tides. An attempt to ascribe the effect to the satellites of *Saturn* proves equally futile.

Moulton next endeavors to answer the question whether the supposed initial conditions could have developed into the existing system. We know that the molecules of a gas are moving about at velocities which increase with the temperature. Near the surface of the original Laplacian nebula the velocities of the molecules, in the case of such light elements as hydrogen, would be so great that the molecules would overcome the power of gravitation and be dispersed in space. It would, therefore, be difficult to account for the abundant supplies of this gas now observed on the Sun. A stronger objection is afforded through the application of these principles to the planets. It is easy to calculate, through the known velocities of gaseous molecules and the masses of the planets, the power of each planet to retain an atmosphere. It is also possible to determine with the spectroscope whether atmospheres exist on the planets. Working in this way, Moulton shows the improbability that the diffuse Earth-Moon ring, with its low power of attraction, could have held any of the atmospheric gases or water vapor, when such concentrated bodies as the Moon and *Mercury* are unable at the present time to hold atmospheres.

As we know the masses of the Sun and planets, the average density of the original nebula, when it extended to the orbit of *Neptune*, can be approximately calculated. Moulton finds this to be about $\frac{1}{191000000000}$ of that of water.

In this extraordinarily rare nebula, whether truly gaseous or meteoroidal, it is shown that matter would have been left behind continually and that the formation of separate rings would be impossible—a conclusion reached by Kirkwood in 1869. Moulton thinks it equally certain that a large mass could not have been detached by any fission process. Furthermore, even if a ring had been formed, he shows it to be utterly improbable that its matter could have been drawn together into a planet.

Some of the above conclusions may perhaps be open to question, but the final argument seems to be unanswerable. It is a well-known principle of dynamics that the moment of momentum of a system of bodies not under the action of external forces is constant. The moment of momentum is defined by the sum of the products of the masses of all the particles by their velocities and by their distances from the center of the system. This quantity should remain absolutely unchanged, whether the system be in the form of a nebula occupying the whole of *Neptune's* orbit, or a group of planets revolving around the Sun. Making his assumptions in such a way as to be most favorable to the nebular hypothesis, Moulton obtains the following results for the moment of momentum:

When the nebula extended to *Mars'* orbit	M=32.176
When the nebula extended to *Jupiter's* orbit	M=13.250
When the nebula extended to the Earth's orbit	M= 5.690
When the nebula extended to *Mercury's* orbit	M= 3.400
In the system at present	M= 0.151

Thus, instead of remaining constant, the moment of momentum is shown to decrease rapidly and irregularly. In spite of the precautions taken to favor the nebular hypothesis as much as possible, the moment of momentum of the original system comes out 213 times that of the present solar system.

The papers of Chamberlin and Moulton contain other serious criticisms based upon the study of the moment of momentum of the system, and raise various additional difficulties. Thus the attenuated state of the rock-forming substances of the Earth in the Earth-Moon ring would probably have resulted in their condensation into solid particles. Again, no nebulae closely resembling the annulated solar nebula have yet been discovered. Without going further into details, and without necessarily admitting the finality of all the above arguments, it can hardly be denied that Laplace's idea of the development of the solar system must be reconstructed or abandoned. It remains to be seen what can be substituted for it. Two attempts in this direction will be described in a later chapter.

CHAPTER XX

STELLAR DEVELOPMENT

THE nebular hypothesis, as outlined in the last chapter, presents a picture of the development of a planetary system like our own. In testing it, recourse may be had both to theoretical investigations and to observations of various kinds, particularly of nebulae, which may throw light on the earlier stages of the process of condensation. It must be remembered that planets comparable in size with the members of our solar system would be quite invisible at the distances of the stars. However, in the study of stellar evolution we are concerned primarily with stars, rather than with the planets that may accompany them. It is nevertheless evident that the two questions cannot be considered independently, since the details of the processes that result in the formation of planets must be of the highest importance in researches on the development of the central suns of which they may have formed a part.

Herschel, whose mind was always occupied with the problem of the structure of the universe and the formation of its individual members, thought he perceived in the nebulae evidences of growth and development. He supposed that the cloud forms, of irregular structure, which extend over vast regions of the heavens, represent the earliest and most rudimentary condition of stellar life. Condensation toward a center, brought about by the action of gravity, would be shown in such a cloud by increased brightness. Latest in the line of nebular existence Herschel placed the planetary nebulae, in whose symmetrical forms he saw illustrated some such condition as Laplace postulated for the primitive solar system.

The mystery of the planetary nebulae still remains unsolved, but evidence is lacking that they represent a more advanced state than such irregular cloud masses as the Great Nebula in *Orion*. Indeed, it must be admitted that the accumulation of observations, principally through the aid of photography, has rendered the problem of nebular development more complex than it appeared to Sir William Herschel. Thousands of nebulae, entirely unknown to him, have been brought to our knowledge through improvements in telescope design and the aid of the sensitive plate. These range in character from immense luminous tracts, such as are shown, intermingled with stars, in photographs of the Milky Way, to the definite outlines and highly suggestive structure of the spiral nebulae. Of all objects in the heavens these latter most strongly suggest the operation of some process of development. But not a single object of this type was known to Herschel, and even to this day their enormous distance from the Earth has prevented the detection of any changes in form, which might point to the explanation of their origin.[1]

If we follow Herschel, and consider the simplest case of nebular development, we may suppose that through loss of heat by radiation a portion of a nebulous mass begins to condense toward a center. Although still wholly gaseous, and showing few points of difference from an ordinary nebula, we may regard such an object as representing the first period in the life of a star. In the heart of the *Orion* nebula, Plate XXI, are four small stars, which constitute the well-known *Trapezium*. Situated as they are in this enormous mass of gas, it is not difficult to picture them as centers of condensation, toward which the play of gravitational forces tends to concentrate the gases of the nebula. It might therefore be expected that stars in this early stage of growth

[1] See chap. xxi.

would show, through the spectroscopic analysis of their light, some evidence of relationship with the surrounding nebula. Now, this is precisely what the spectroscope has demonstrated. Not only these stars, but many others in the constellation of *Orion*, are shown by the spectroscope to contain the same gases that constitute the nebula. Moreover, they also partake of its motion through space. Finally, Frost and Adams have demonstrated the interesting fact that some of these stars are actually moving in orbits about dark companions situated in the very heart of the nebula. Since the orbital velocities of the moving stars are very high, it thus seems probable that the matter which constitutes the Great Nebula in *Orion* is exceedingly tenuous, offering little resistance to motion within it.

Other examples of direct relationship between stars and surrounding masses of nebulae might be mentioned, but this one will suffice for our present purpose. We must now consider what changes in color and in spectrum accompany the further development of the star as it continues to lose heat through radiation.

Fraunhofer was the first, in the opening years of the nineteenth century, to observe the spectra of the stars. The simple method he employed, which consisted in placing a prism over the object-glass of a telescope, has since become, through the skill and energy of Pickering, a wonderfully effective agent for the wholesale study of stellar spectra. To Fraunhofer the differences he perceived when comparing the spectra of different stars were of no meaning, since the work of Kirchhoff had not yet been done. But the photographs made under Pickering's direction at the Harvard College Observatory now tell a remarkable story to the initiated. In making these photographs, a large prism is mounted in front of the object-glass of a (refracting) telescope, which is directed to a field of stars

and made to follow its apparent motion by a driving-clock. Under these conditions, each star-image in the field of the telescope is drawn out into a spectrum, which falls upon a photographic plate at the focus. If the rate of the driving-clock were perfect, each of these spectra would be extremely narrow, and the "lines" which cross it might not be perceptible. To give the spectra the necessary width, the prism is set with its refracting edge parallel to the diurnal motion, so that the spectra would drift on the photographic plate, if the telescope were at rest, in a direction at right angles to their length. In making the photographs, the rate of the driving-clock is slightly altered, so that the drift of the spectra during the exposure is just sufficient to give them the desired width. Without this drift, each "line" would be merely a point in the spectrum. Plate LXXIX illustrates how admirably the spectra of the various stars in the field are recorded, and brings before us evidence of the spectral diversity which is supposed to characterize the different stages of stellar growth.

As already indicated (chap. xviii), the spectra of stars increase in complexity as the cooling process continues. The gaseous nebulae contain a few bright lines in their spectra, the most conspicuous one of which belongs to a gas ("nebulum") not yet discovered on the Earth. The other nebular lines are due to hydrogen and helium. Those stars of the "*Orion* type" which appear to be earliest in order of development contain no lines except those of hydrogen and helium, which are faint and very broad and diffuse. As these gases are found in the gaseous nebulae, and as the relationship of these stars to surrounding nebulous matter is otherwise apparent, there is every reason to believe that they represent the earliest phase of stellar life. The stars of the *Trapezium*, which have already been mentioned as organically related to the Great Nebula of *Orion*, are of this type. "*Orion*" stars

which appear to be somewhat further developed, show lines of magnesium, silicon, oxygen, and nitrogen, in addition to those of hydrogen and helium (Plate LXXX).

Next in order of evolution appear to be the white, or bluish-white, stars like *Sirius* (Fig. 1, Plate LXXXI). The spectrum of *Sirius* is marked by broad and conspicuous hydrogen lines, associated with narrow and faint lines of iron, sodium, magnesium, etc. It has been shown by investigations of certain pairs of stars, in which the two components are in rapid rotation about their common center of gravity, that stars like *Sirius* are much less dense than the Sun, their specific gravity not exceeding that of water. This, of course, is exactly what would be expected in an early stage of transition from a gaseous nebula to a highly condensed star.

It is well known through mathematical demonstration that the condensation of such a mass of gas as that in which the Sun originated must involve the production of a vast amount of heat. Indeed, the present solar radiation may be accounted for by supposing that the Sun's diameter decreases about 400 feet in the course of a year. The seemingly paradoxical fact that a gaseous mass, through loss of heat by radiation, will actually grow hotter as long as it remains in a gaseous condition, was demonstrated by Lane in 1870. The point is that the heat produced by shrinkage is more than sufficient to compensate for the loss by radiation. Consequently, the shrinking mass grows hotter as long as it remains purely gaseous. The time finally comes, however, when its outer parts, which radiate freely into space and are not protected from loss by outlying masses of heated matter, are cooled to the point of condensation. That is to say, certain metallic elements present in a state of vapor condense into clouds made up of minute liquid drops, thus resembling our terrestrial clouds, which are caused by the condensation of water vapor.

When this point is reached, radiation must take place mainly from the surface of the star. This would result in very rapid surface cooling, were it not for convection currents, which rise from the interior and supply the heat lost by radiation. In the Sun we have strong evidence of the existence of such currents, which are represented by the bright filaments that constitute the granulated surface (chap. xi), and by the minute flocculi illustrated in Plate XXXIX. The darker spaces (pores) between the granulations probably represent the cooler descending vapors. The denser vapors, which perhaps occupy these darker regions, apparently lie below the general photospheric level, for it has recently been found at Mount Wilson that the spectrum of the Sun's disk, at points very near the limb, differs decidedly from the spectrum at the center. The hazy wings, which may be seen on either side of many lines photographed at the Sun's center, and are still more conspicuous in sun-spots, are greatly reduced in intensity at the limb (Plate LXXXII). This would seem to indicate that at the center of the Sun we are looking down into the regions between the granulations, to a level where the vapor is dense enough to produce the winged lines. Near the edge of the Sun, on the contrary, we look across the tops of the bright filaments, and therefore fail to receive light from the denser vapors below. The absorption of the higher and cooler vapors should produce a change in the relative intensities of the lines such as takes place in sun-spots (p. 159), but in much smaller degree. Observation shows this to be the case, but there is by no means a strict parallel between the two classes of phenomena, and judgment must be reserved for the present. One of the next steps will be to photograph the spectrum of a pore, if so minute an object can be separately observed. The investigation, when completely worked out, should furnish a searching criterion as to the validity of the hypothesis of

reduced temperature in spots, and as to the cause of certain phenomena in the Sun and stars.

We have already seen (p. 173) that increased density of the absorbing atmosphere tends to reduce the proportion of violet and ultra-violet rays, and thus to introduce a yellowish or reddish tinge into the star's light. Such stars as *Sirius* do not possess dense absorbing atmospheres, and because of this fact and of their extremely high temperature, their spectra extend far into the ultra-violet.

In passing from these white stars to the yellowish stars, which constitute the solar class, the continued process of condensation is accompanied by the production of an absorbing atmosphere similar to that of the Sun. Beginning in the ultra-violet, the absorption becomes more and more appreciable as the solar type of star is approached. The decrease of intensity, while most marked in the ultra-violet region, is also manifest in the blue and violet part of the spectrum, whereas the red, yellow, and green are not greatly affected. The natural result is a change of color, through a deficiency in blue light. For this reason, stars of the solar class are yellowish in hue. Langley has pointed out that the Sun would appear bluish-white, if its absorbing atmosphere were removed. Accompanying this change of color we have the decreasing strength of the hydrogen lines, and the increasing strength of the metallic lines, which become very numerous in *Procyon* (Plate LXXXI) and still more so in the Sun.

As already remarked, this gradual increase of atmospheric absorption prevents us from basing conclusions as to relative stellar temperatures on the position of the maximum of intensity in the spectrum. We may fall back, however, upon comparisons of the relative intensities of certain lines, just as was done in the study of sun-spots described in chap. xvii. This method of classifying stars according

to their temperature was applied by Lockyer many years ago. He found that the "enhanced lines," which are brightest in the spark spectrum of a metal, exist alone in certain stars. In other words, the arc lines of the same metal, which are strong at the lower temperature of the arc, and feeble or absent in the spark, are so much reduced in intensity in these stars as to be entirely invisible.

Lockyer's contention that these changes of relative intensity afford a mode of classifying stellar spectra on a temperature basis was denied by many spectroscopists, because of the possibility that such changes might be produced in stars by different electrical conditions rather than by differences of temperature. The results obtained in our laboratory imitation of sun-spot phenomena, however, seem to favor the view that a temperature classification of stars, on the basis of the relative intensities of lines, is perfectly possible. For in these experiments it was shown that when all electrical phenomena are excluded, a decrease in temperature of the radiating vapors is accompanied by an increase in intensity of the lines that are strengthened in sun-spots and in red stars. Since the spark lines are weakened under the same conditions, and since conclusive evidence of comparatively low temperature is afforded by the presence in these spectra of flutings due to substances which are broken up at the higher temperature of the Sun, the temperature hypothesis may perhaps be taken as affording a simple basis of classification. This statement is not made without some reservations, however, as indicated by the remarks at the end of this chapter, and by the discussion of Lockyer's meteoritic hypothesis in chap. xxi. Moreover, since this classification takes no account of the possible effect of mass and environment on spectral type, it is hardly likely to prove adequate.

Let us now consider the phenomena of declining stars,

which have passed beyond the solar stage and are fading into invisibility. It will be remembered that these stars are orange or red in color and that they may be divided into two classes, similar in appearance to the eye, but easily distinguishable with the aid of the spectroscope. The first of these classes (Secchi's third type) includes certain bright stars, such as the red *Antares*, which is a conspicuous object in the southern heavens during the summer months. The second class (Secchi's fourth type) has no brilliant representative. Indeed, the brightest stars of this character are but barely discernible by the naked eye, while the great majority are to be observed only with the aid of a telescope.

In the spectroscope both classes show a spectrum vastly more complicated than that of stars in an earlier stage of growth. The broad lines of hydrogen, which are greatly reduced in intensity in the Sun, are still further reduced in the red stars. In fact, the dark hydrogen lines have in certain red stars given place to bright lines, especially in the case of variable stars, whose light undergoes regular or irregular fluctuations. The most characteristic feature of the red stars, however, is the presence in their spectra of dark bands or flutings. In third-type stars the sharp edges of these bands lie toward the violet, while on the red side the intensity gradually decreases. These bands have been found by Fowler to be due to the oxide of titanium, which may be broken up at the higher temperature of the Sun, but exists in the spectra of sun-spots (Plate LXXIV). The bands of the red stars of Secchi's fourth type face in the opposite direction, with their sharply defined boundaries toward the red. These bands, as Plates LXXXIII and LXXXIV illustrate, are due to carbon and cyanogen. Some of them are faintly present in the Sun, but in the fourth-type stars they are much more strongly developed.

The extensive investigations of Vogel and Dunér, made visually, have given us much information regarding the spectra of the red stars. However, the fourth-type stars are so faint that only the bands in their spectra could be seen with the telescopes used by these investigators, and their numerous dark lines were beyond observation. The great light-grasping power of the Yerkes telescope rendered a photographic study of these spectra possible, with the results shown in Plates LXXXIII, LXXXIV, and LXXXV. When the fourth-type stars are ranged in a series, the gradual change of spectrum from star to star is well illustrated (Fig. 2, Plate LXXXIII). The carbon flutings become stronger and stronger, until in a star like 152 *Schjellerup* they are so dense that they cut out a considerable portion of the light. In the Sun, the Yerkes telescope shows the existence of a very thin layer of carbon vapor, lying in close contact with the photosphere. In the fourth-type stars we may suppose that the further process of condensation results in an increased development of carbon vapor, the absorption of which becomes the characteristic feature of the spectrum.

Another important point brought out by this investigation is the close relationship existing between the line spectra of third- and fourth-type stars. As will be seen by an examination of Plate LXXXV, the line spectra of μ *Geminorum* and 74 *Schjellerup* seem to be almost precisely identical in certain regions. The presence of titanium oxide bands in the one case, and the carbon flutings in the other, complicate the comparison of the line spectra in other regions, though much is yet to be learned on this subject through further study of these stars with spectrographs of the highest dispersion.

In view of the resemblance of the line spectra, it is difficult to understand the diversity of the band spectra in the two great classes of red stars. Among third-type stars all

intermediate types of spectra may be found between the Sun and the most advanced representative of the class. It might thus seem, especially in view of the close relationship between sun-spot and third-type spectra, that the cooling of the Sun would result in the formation of a third-type star. However, although no such perfect continuity has been shown to exist in the transition from solar to fourth-type stars, it seems possible that stars intermediate in character between 280 *Schjellerup* (see Plate LXXXV) and the Sun may yet be discovered. Should this prove to be the case, and a more rigorous test be found to confirm the observed resemblance of the line spectra of the third and fourth types, the question whether a star like the Sun will develop into a third- or into a fourth-type star would be difficult to answer. This problem, which is one of the most interesting of those connected with the study of stellar evolution, will occupy a prominent place in the working programme of the Solar Observatory.

Although the red stars represent the last period of luminous stellar life, there remain to be considered the dark stars, which have been discovered in spite of their complete invisibility. Hundreds of these objects are already known to us through spectroscopic observations. They are members of double or triple systems, moving in orbits about a common center of gravity. Their existence has been inferred from measurements of the oscillation of the spectral lines, which move back and forth toward the red or toward the violet, as the star under observation recedes from and then approaches the earth in its orbital motion. Obviously, it is the spectrum of the visible star which can be observed, but motion in an orbit necessarily implies the existence of a companion star, which may or may not be luminous. If sufficiently bright to be visible, it may not be separated from its close neighbor in the most powerful telescopes. But in the spectroscope

the lines of the composite spectrum will appear double, twice in each orbital revolution of the pair. If only one star is bright enough to give a spectrum, its lines will simply oscillate to and fro.

Hitherto we have tacitly assumed, in harmony with current views, that all stars are built on a single model, and that each passes through the same stages of development in its transition from the nebular condition to the solid state. It should be pointed out here, however, that many circumstances warn us against implicit acceptance of such a law of uniformity. The assumption that a given type of spectrum represents a given stage of growth involves the idea that the chemical composition of all stars is essentially the same, and that the particular position of the star in the universe, and other conditions which may obtain in individual cases, are matters of no importance. While it is true that we have strong reasons for belief in the universal distribution of most of the chemical elements known on the Earth, and the universal operation of the law of gravitation, and of all other laws which define terrestrial conditions, the assumption that identically the same course is pursued by every star in passing from its origin to its final decay is entirely unwarranted. We must be prepared to meet widely diverse conditions and to observe modifications in the process of development which are determined directly by such conditions.

Take the case of the *Pleiades*, for example (Plate LXXXVI). Here we have a group of stars entangled in nebulosity, and moving together through the heavens. Every indication goes to show that this is an organic group, whose members are of common origin. But the spectra of practically all of these stars, irrespective of size and brightness, are of Secchi's first type. How are we to believe that widely different masses will pass through their evolutional

steps with equal rapidity? An appeal to double stars, whose members are undoubtedly of common origin, does not help matters. We invariably find that the fainter member of the system, which might have been supposed to cool most rapidly because of its smaller size, is yellow or red in color, while its larger companion is more nearly white, or tinged with blue. Huggins argues, however, that the greater surface gravity possessed by stars of large mass may cause more rapid change in spectral type. Thus a large star of low density may be no farther advanced in spectral type than a smaller but more highly condensed star. According to Huggins' views, the early steps in evolution would be characterized by small gravity at the surface, comparatively slow changes of temperature in passing outward from the interior, and convection currents less violent than those observed in the Sun. If the star were hot enough, hydrogen might be the only gas sufficiently cool, with respect to the radiation from below, to show itself by absorption lines. Vapors of greater density would lie lower in the star, where their temperature might be so nearly that of the region behind them that their lines would not appear in the spectrum.

Schuster, who has done an important service in emphasizing the elements of weakness in the assumed law of uniformity, nevertheless believes that most of the spectral types represent stages in the development of stars. Thus, while he does not maintain that all stars pass through an identical series of changes, he agrees with the view that the general course of development lies along similar lines, though important modifications may enter in particular cases. The order of development which he favors is as follows:

(1) Helium or *Orion* stars.
(2) Hydrogen or *Sirian* stars.
(3) Calcium or *Procyon* stars.
(4) Solar or *Capellan* stars.

In describing the process of condensation, Schuster points out that the expansion caused by the rising temperature of the gaseous bodies must at first result in the rejection of helium, hydrogen, and other light gases, on the supposition that the gravitation is not sufficient to retain them. These light gases will thus be left to constitute diffuse nebulous masses, as illustrated by the gaseous nebulae, particularly by the nebulous regions in such a group as the *Pleiades*. In the process of time, however, the star will have condensed sufficiently to retain hydrogen and helium, and these gases will then begin to diffuse into the interior, where they will be absorbed at a rate which depends upon the star's mass. Helium, which is denser than hydrogen, will be retained first, thus giving rise to the helium, or *Orion*, stars. As this gas diffuses inward, its place will be taken by hydrogen, which will thus become predominant in the spectrum. In its turn, the hydrogen will diffuse into the star, and the increasing convection currents will cause a more and more complete stirring-up of the low-lying metallic vapors, which will therefore play an increasingly prominent part in the spectrum. Thus the solar stage will ultimately be reached.

An interesting point in this explanation is the considerable possibility of variation which stars of different mass and in different environments may exhibit. If but little hydrogen happens to be in the neighborhood, the process of condensation may not result in the attraction of a sufficient quantity of this gas to produce the hydrogen type of spectrum. Again, the star may be of such low density that it is unable to attract hydrogen, and thus it may pass into the solar stage without exhibiting strong hydrogen lines. There may also be stars of such small mass that, in spite of having condensed sufficiently to attract hydrogen, they are not able to absorb it all, and therefore they may continue to exhibit a spectrum of the first type without ever passing into the

solar stage. Furthermore, in the case of two stars of equal age but different mass, the larger may have passed to the condition of *Arcturus* (incipient red star), while the other is still in the solar stage, because of its more rapid absorption of hydrogen.

This theory gives an interesting explanation of the above-mentioned spectral phenomena of double stars, since it indicates that the larger star, through its power of absorbing hydrogen more rapidly and completely, may pass to the solar stage, while the smaller one continues to give a spectrum of the first type. Schuster agrees with Huggins that the small mass would lose heat more rapidly than the larger one, but believes that the type of spectrum may be more completely controlled by the rapidity with which the hydrogen is absorbed.

It is evident that the highly suggestive views of Schuster should stimulate much research. The distribution of spectra of different types through the heavens is a subject of great interest, and doubtless has an important bearing on the question of stellar evolution. Certain types of stars, for example, tend to cluster thickly in the Milky Way, while others show no such tendency. Pickering's work in photographing the spectra of an immense number of stars in the northern and southern heavens offers most valuable material for the study of this subject. The investigation may perhaps be extended to fainter stars with the 60-inch Mount Wilson reflector, through the use of a spectrograph having no slit and so designed as to record photographically the spectra of all stars lying within a certain field. But since this field can hardly exceed 20′ of arc in diameter, it would not be feasible to photograph the entire heavens in this way.[1]

However, a most important scheme of co-operation has been instituted by Kapteyn, for the purpose of obtaining

[1] The objective prism photographs cover a field several degrees in diameter.

data bearing upon the problem of the geometrical stucture of the universe and the distribution of stars within it. Through the impracticability of securing all necessary data for stars distributed over the entire heavens, Kapteyn has selected certain limited areas of the sky, so distributed as to render it probable that conclusions based upon a complete study of the stars within these areas will be likely to apply to the heavens at large. The application of the 60-inch reflector to the photography of stellar spectra by the above-mentioned process will therefore be confined, for the most part, to Kapteyn's areas, where many other observers are already gathering information, in accordance with a plan which allots to each institution the work for which its instruments are best adapted. For Kapteyn's purposes, only the general type of spectrum is required, since he is primarily concerned with questions of distribution and structure, rather than those which relate to the evolution of stars. The data he desires include determinations of the brightness, distance, and motions of the stars within the selected areas. The 60-inch reflector, on account of its great light-gathering power, can assist materially in those portions of this work which relate to the faintest stars. The investigation of the motions of these stars in the line of sight is necessary from the evolutional standpoint, because community of motion may mean organic relationship of stars in a group, as in the case of the *Pleiades*. Photometric investigations and the study of parallaxes are also required, since, when the distance and brightness of a star are known, its mass can be determined, if certain reasonable assumptions as to the surface brilliancy are made. We have just seen how important a factor the mass of a star may be in determining the course of its evolution.

Enough has been said to indicate the nature of the work which large telescopes may perform. The direct photography

of nebulae may provide the means of detecting, in the course of years, changes in their form bearing directly upon the manner and rate of their condensation. The photographic study of their spectra may help to explain why a few nebulae show the bright line spectra of gases, while the very numerous spiral nebulae appear to have merely a continuous spectrum. With the high dispersion of powerful spectrographs like the one shown in the constant-temperature chamber in Plate XCVI, the spectra of a few of the brightest stars in the heavens, which include most of the spectral types, can be minutely analyzed. In this way, and with the aid of smaller spectrographs, the spectra of red stars of the third and fourth types can be examined to much better advantage than previously, with reference to their relationship to the Sun, to sun-spots, and to one another. It is evident that these investigations, with others on the spectra of stars of various classes, the distribution of the different types of spectra within Kapteyn's selected areas, and studies of the brightness and parallaxes of the same stars, might well involve the co-operative use of several telescopes of the largest size.

CHAPTER XXI

THE METEORITIC AND PLANETESIMAL HYPOTHESES

In even the briefest outline of the methods of studying stellar evolution, reference must be made to two hypotheses which are intended by their authors to take the place of the nebular hypothesis of Laplace. In both of these, swarms of meteorites, rather than matter in the gaseous state, are supposed to afford the raw material of which stellar systems are compounded. The nature of the swarms, however, is unlike in the two cases. According to Lockyer, the meteorites are to be regarded as analogous to the wandering molecules of gases, in that they move indiscriminately in all directions and at widely different velocities. Sir George Darwin has, indeed, demonstrated mathematically that a meteoritic swarm, constituted in this way, is closely analogous to a gas. The meteorites move rapidly about, colliding with one another from time to time, just as the molecules of a gas are supposed to do, according to the kinetic theory. Chamberlin and Moulton, on the contrary, assume their meteorites to be revolving in well-defined orbits, and therefore suffering only such collisions as may result from certain meteorites overtaking others of lower velocity.[1]

The most characteristic nebular line is a brilliant one in the green part of the spectrum, attributed to an unknown gas, which has been called "nebulum." According to Lockyer, this line is the remnant of a complicated fluting in the spectrum of magnesium oxide, with the brightest part of which he found it exactly to coincide. In his view

[1] In his explanation of globular and spiral nebulae, and of certain other celestial pheuomena, Lockyer also assumes the meteorites to revolve in well-defined orbits.

the rest of the fluting is invisible only because of the faintness of the nebular line. This has been completely disproved, however, by Keeler's remarkably precise measures of the chief nebular line at the Lick Observatory. His observations show, not only that the chief nebular line does not correspond in position with the head of the magnesium fluting, but also that it differs entirely from it in appearance. It is therefore not possible to regard magnesium oxide as a constituent of the nebulae. The green line may with far greater probability be considered to represent a very light gas, not yet discovered on the Earth.

Lockyer's conclusions as to the origin of the chief nebular line play an important part in his meteoritic hypothesis. He believes that the frequent collisions between meteorites in the swarms produce sufficient heat to volatilize certain constituents of the meteorites, which are rendered luminous, so that their lines should appear in the nebular spectrum. Lockyer tried the experiment of heating fragments of meteorites in a tube, from which the air had been partially exhausted. He found that hydrogen, hydrocarbon vapors, and the vapor of magnesium oxide were given off from the meteorites. When an electric discharge was passed through the gases in the tube at reduced pressure, the spectrum was found to consist of the lines of hydrogen, the characteristic flutings given by compounds of carbon, and the green fluting of magnesium oxide, to which reference has been made. In comets, which are known to be intimately associated with meteorites, the flutings due to compounds of carbon form the most characteristic feature of the spectrum. But although certain astronomers have believed these flutings to be present in the spectrum of the nebulae, their conclusions are not confirmed by the majority of observers, who can neither see nor photograph any trace of the flutings. The only remaining connection between the nebulae and the gases

derived by Lockyer from meteorites therefore depends upon the presence of hydrogen in both cases. But hydrogen is so universally distributed among the celestial bodies that its absence from nebulae would almost be regarded as an anomaly requiring explanation. It therefore cannot be said that much weight is to be accorded to the experimental basis of the meteoritic hypothesis.

It ought to be said, in favor of the hypothesis, that it provides a simple way of accounting for the existence in the nebulae of substances not represented in their spectra, but which appear in stars evolved from nebulae. If a nebula is to be regarded as a glowing gas, in which all substances contained in stars exist in a state of vapor, it remains to be shown why a very few gases manifest their presence by the appearance of their bright lines in the spectrum, whereas all the other elements produce no lines, and therefore give no indication of their existence. In this connection it must not be forgotten that in mixtures of various vapors the spectra of some of the vapors appear when an electric discharge is passed through the mixture, while the lines due to certain other vapors remain invisible. Too little has been done, however, in this important field of research, to permit final conclusions to be drawn. For this reason no one is at present able to say in what form the iron, nickel, and other metals, which subsequently make their appearance in the stars, can exist in the nebulae.

This question is, indeed, but one of the many mysteries which at present surround the nebulae (Plates LXXXVI–XC). We have no knowledge, for example, why they glow with a steady and unchanging light, since there is no direct evidence that this light is produced either by heat or by electrical excitation. It must not be forgotten that very few nebulae are certainly known to be gaseous: thousands of

them seem to give a continuous spectrum, in which the bright lines of gases do not appear. Whether this is due to the presence of solid or liquid matter, to pressure effects, or to other causes, is not yet known. The process by which stars are condensed out of nebulae is also not clearly understood. It cannot depend wholly upon some action connected with the spiral form, since, as already stated, we have in the *Orion* nebula, which is not a spiral, one of the best-known examples of direct relationship between stars and nebulae. It is now rather commonly believed that, while the temperature of small particles in the nebulae may be very high, the mean temperature of the entire mass may nevertheless be very low, since it has been pointed out by Huggins that the appearance presented by the nebulae could be produced by widely separated luminous particles. In view of all these facts, it may therefore be said that much work remains to be done on the nebulae, not only in photographing their forms, but in investigating their spectra, and in interpreting them through laboratory experiments.

Starting from the meteoritic hypothesis, and assuming that the chemical elements, at the temperature of the hottest stars, are dissociated into simpler substances, Lockyer has developed a plan of stellar evolution which comprises a classification of stellar spectra on a temperature basis. He supposes that the meteoritic swarms represented by the nebulae gradually condense into stars, by processes whose details are still uncertain. According to his classification, the gaseous and bright-line stars, in which the temperature is supposed to be higher than that of the less condensed nebulae, lie just above the latter in point of development. Then come the red stars of Secchi's third type: though it may appear to many spectroscopists that the difficulty of tracing a connection between their spectra and those of the stars placed just before them would be altogether insuperable. Further conden-

sation, still involving a rise of temperature, would produce stars analogous to the Sun, but differing in the important particular that, while their temperature is increasing, that of the Sun is supposed to be decreasing. Finally, at the point of maximum temperature, Lockyer places stars of Secchi's first type. Here the meteorites, long since completely transformed into the gaseous state, have reached the condition implied by Lane's law, at which the rise in superficial temperature, due to continued condensation, is just balanced by the loss resulting from radiation. The declining period, then setting in, results in the development of stars like the Sun, which can be only arbitrarily distinguished from stars of equal, but rising, temperature, lying on the opposite branch of the temperature curve. After the solar stars come the red stars of Secchi's fourth type, and after these, final extinction of light.

This system of classification, considered apart from the hypotheses with which it is connected, has the advantage of providing for both the ascending and descending branches of the temperature curve. Unfortunately, we are perhaps not yet in a position to distinguish clearly between stars of the same surface temperature, in one of which the gain of heat is more rapid than the loss, while in the other the reverse is true. As already remarked, the assumption that the red stars of Secchi's third type lie not far above the nebulae is also a difficult one to admit. But the classification nevertheless deserves careful consideration, and the most searching tests that can be applied.

As the late Miss Clerke has well said, the complex structure of meteorites suggests a highly developed, rather than an elementary, condition of existence. This, however, is hardly to be taken as an objection to Lockyer's hypothesis, since the manner in which the meteoritic swarms came into existence is not postulated. The planetesimal hypothesis, however,

begins with a fully organized sun, which is supposed, in its motion through space, to come into the immediate neighborhood of another sun, equal to or greater than itself. The effect of the attraction between the two bodies would be to reduce the immense restraining power of the Sun along the line of mutual attraction, *i. e.*, in the direction of the other sun, and in the opposite direction. Under certain conditions the Sun is observed to shoot out prominences with velocities approaching 300 miles per second. If the velocity exceeded 382 miles per second, the matter projected from the Sun would escape the power of its attraction and move off into space, never to return. If another great body were passing near the Sun, the tendency toward eruptions would be greatly augmented along the line joining the two bodies, and immense protuberances would doubtless be projected at high velocities from opposite ends of the solar diameter corresponding with this line.

According to the planetesimal hypothesis, the two protuberances would be formed as the two suns were swinging past one another around their common center of gravity. The effect of mutual attraction would be to cause the two great arms to assume a spiral form, in which the scattered materials revolve about the central mass in elliptical orbits. Moulton has shown, by rigorous mathematical tests, that just such a result might actually occur, and that the forms of the spiral nebulae may thus be closely imitated (Plates LXXXVIII–XC). Although the matter shot out from the Sun would necessarily be gaseous, the hypothesis assumes that it would rapidly cool down to a finely divided solid condition.[1] The outer portions of the protuberances would naturally be formed from the surface materials of the Sun, while the inner extremities would come mainly from lower

[1] How, it may be asked, can these small bodies remain brilliantly luminous for many years? And why do we not discover incipient spirals, giving a bright line spectrum?

depths, where the heavier elements are found. This may possibly explain the lightness of the outer planets of our solar system, and the great relative weight of the inner ones. The changing attraction of the neighboring star might also cause a series of irregular outbursts, accounting for the knotty and uneven distribution of the matter in the spirals (Plate XC). Chamberlin points out that a very small fraction of the Sun's mass, not exceeding 1 or 2 per cent., would be amply sufficient to supply all of the matter required to form a planetary system like our own.

In the further evolution of the system, the central mass is supposed to form the sun, the knots to serve as the nuclei about which the planetary materials gather, and the remaining diffuse nebulous matter to be swept up by the nuclei or absorbed by the sun. The building-up of the planets is not supposed to take place, as in the nebular hypothesis, simply through the gravitational attraction of the planetary nuclei on the matter surrounding them. On the contrary, the main agency is assumed to be a gradual accretion of the mass through collisions of isolated planetesimals (meteorites) resulting from the intersection of the individual orbits, brought about periodically through the rotation of their line of apsides. Thus it is held, according to this hypothesis, that the Earth was never a molten mass, but that it was built up by gradual accretions. Chamberlin was led to this view of the condition of the Earth's interior from various geological considerations, which seem to him inconsistent with the hypothesis of a fluid origin.

If this book were a treatise on stellar evolution, all of these questions would require much fuller discussion and criticism, and space would necessarily be devoted to the remarkable phenomena of variable and temporary stars, the tidal investigations of Darwin and their possible bearing on the evolution of double-star systems, and many other subjects

which have not received consideration. Enough has been said, however, to give an idea of the nature of the problems which an observer concerned with stellar evolution is called upon to attack, and the general character of some of the observational methods required to solve them.

CHAPTER XXII

DOES THE SOLAR HEAT VARY?

ONE does not often stop to think of the delicate balance that determines the conditions of life on the Earth. But it is obvious enough that a small change in the intensity of the solar radiation would suffice to transform the climate of the temperate zones to that of the equatorial or polar regions. A greater change might soon result in the complete destruction of life.

It is therefore a matter of the most vital interest to inquire into the source and constancy of the Sun's heat. What fuel maintains the great fire that warms and lights us, and supplies, through its beneficent influence on growing crops, the food that we consume? Is the average daily influx of solar rays constant and unchangeable, and are we justified in our tacit belief in the inexhaustibility of the supply? Such thoughts, seriously pondered by students of solar physics, have led to extensive investigations, which must go on for many years before these questions can be finally answered.

As we have already seen, the contraction of a nebulous mass to form a star, or a sun like our own, must result in the liberation of much heat. Indeed, the total solar radiation in the course of a year can be accounted for on the supposition that the Sun's diameter decreases about 250 feet in this time. Since the discovery of radium, which possesses the remarkable property of sending out heat, with little evidence of exhaustion, for very long periods of time, it has been suggested that this substance, if it exists in the Sun, may be the source of part of its radiation. Radium has not

yet been detected in the Sun with the spectroscope, but it may lie at low levels, where its vapor would take no part in the absorption that produces the lines of the solar spectrum. The abundance of helium in the Sun suggests that radium, which gives off this gas during the disintegration process, may perhaps exist within or beneath the photosphere.

If radium really supplies any considerable part of the Sun's heat, its ultimate exhaustion would involve a decided decrease in the solar radiation. As we are not yet certain, however, that there is any radium in the Sun, the possibility of such a contingency may be regarded as too remote for profitable speculation.

We may take it for granted that the Sun will continue to radiate heat, at practically the present average rate, for many centuries to come. But do we know that the rate is absolutely constant? May not fluctuations occur of sufficient magnitude to affect our climate appreciably, and to be reflected in the ebb and flow of crops and the price of wheat?

Until a short time ago this question had been tested in only the roughest way. It was known that sun-spots pass through a regular cycle of change, occupying about eleven years. A curve was accordingly drawn, showing the varying number of sun-spots, and compared with a curve representing, for example, the varying price of wheat. As the two were thought to show some correspondence in form, it was held that the price of wheat is determined by the solar activity, as measured by the number of spots.

But the correspondence of the two curves was far from perfect, and might have resulted from mere chance. Rainfall and temperature curves have given results that appear more satisfactory, but the whole question is still in its primitive stages, and little that is absolutely definite and reliable has been learned. The efforts now being made by the Solar Commission of the International Meteorological Committee

may be expected to help matters, but much will depend upon the appliances used to measure the solar radiation, and to determine the amount of heat lost by absorption in the Earth's atmosphere.

The most elaborate study of this question yet made is due to the late Secretary Langley, of the Smithsonian Institution. He long ago recognized that the chief difficulty of the problem lies in the constantly varying absorption of the air above us. If measures of the solar radiation could be made from a point outside of our atmosphere, any observed fluctuations would be due to the Sun itself. But near the level of the sea the difficulties are very great.

To diminish them, Langley led an expedition to Mount Whitney in California. Here, at an elevation of over 15,000 feet, the denser and more variable half of the atmosphere is left below. The precision of the measures was thus greatly increased, but the expedition was not able to remain long enough to determine whether the so-called "solar constant" of radiation is actually a constant, or undergoes changes of an irregular or a periodic character.

Langley strongly felt the importance of continuing this work with the greatly improved apparatus developed by Abbot and others at the Smithsonian Astrophysical Observatory in Washington. He therefore recommended that the Carnegie Institution make provision for further researches of this nature at a mountain station. When the Solar Observatory was established, a co-operative arrangement with the Smithsonian Institution was accordingly entered into, and measures of the solar constant were made daily by Abbot on Mount Wilson during the summers of 1905 and 1906.

The apparatus used in this work is most ingenious. Two independent operations are carried on simultaneously: the direct measurement of the solar radiation with some form of pyrheliometer; and the determination of the atmospheric

absorption, for all the colors of the spectrum, with a bolometer (Plate XCI).

The pyrheliometer, in the form used by Abbot, measures the rise in temperature, in a given time, of a known volume of liquid exposed to the Sun's rays. If there were no atmosphere, pyrheliometer measures alone would suffice to furnish the desired information. But the heat of the Sun at noon is far greater than shortly after sunrise, since the rays pass through a much shorter air-path. Consequently, the observations must be repeated at regular intervals throughout the morning.

The bolometer, invented by Langley, is so sensitive to radiation that it will measure a rise in temperature of less than one-millionth of a degree. It consists of two very fine threads of platinum, about $\frac{1}{2500}$ inch thick, mounted side by side within a constant temperature chamber. One of these is shielded, the other exposed to the radiation to be measured. The platinum threads form two of the arms of a "Wheatstone's bridge," and are connected with a storage battery, so that a feeble current constantly passes through them. A galvanometer of the most sensitive type is so balanced in the circuit that its reading is zero when the currents flowing through the two platinum threads are equal. The moment the resistance of the exposed strip is changed by radiation falling upon it, the galvanometer is deflected by an amount which measures the heating effect of the radiation.

In practice, the solar spectrum is caused to move slowly across the exposed bolometer thread. The galvanometer needle then swings back and forth, giving small deflections when a dark line or absorption band is passing over the bolometer, and large deflections when the full intensity of the spectrum is being measured. To record the motions of the needle a minute mirror, attached to it, is caused to reflect a spot of light upon a photographic plate. The same mechan-

ism that moves the spectrum across the bolometer causes this plate to travel slowly downward. Thus the deflections of the needle are photographically registered upon the plate. With the aid of such curves the total atmospheric absorption, measured separately for each region of the spectrum, is accurately determined. The reduced pyrheliometer readings, corrected in this way for absorption, give the value of the solar constant.

With such highly developed instruments the systematic study of the solar radiation was pursued in Washington. On the best days, which came none too often, the refinement of the method permitted the atmospheric absorption to be eliminated, even at this station so near the level of the sea. It was soon found that the values of the "solar constant" were not constant, but variable. Indeed, differences as great as 10 per cent. of the whole were encountered. Was it safe to conclude that the solar radiation undergoes variations of this considerable amount?

On Mount Wilson the escape from the denser air of the valley, the purity of the upper sky, and the constant succession of perfectly clear days, permitted the question to be put to the test. Day after day the Sun was followed through the heavens, from a time soon after it rose above the eastern mountains to its culmination near the zenith. Sometimes the work was continued through the afternoon, but the morning observations proved to be sufficient.

As soon as the curves had been measured and reduced, and the pyrheliometer observations plotted, the full advantages of the mountain station appeared. Not only was the precision of the work much greater than before: even more important was the fact that daily observations, continued for many weeks, brought the exact nature of the phenomenon to light. Through the latter part of the month of July, 1905, the value of the solar constant increased slightly from day

to day, until it reached a maximum. It then declined in the same gradual manner. From these results Abbot concluded that the solar heat had temporarily undergone actual change, not to be ascribed to any modification of our own atmosphere.

Does this mean a greater outpouring of the solar radiation, caused by an actual increase in the surface temperature of the Sun? Or had the absorption of the solar atmosphere decreased for a time, returning later to its normal value? Much study will be required to answer this question, though the uncertainties may be partially cleared up when the 1906 observations have been reduced. Increased solar activity, represented by numerous sun-spots and flocculi, may probably be taken to indicate the existence of more numerous and more violent convection currents, bringing larger quantities of heat from the Sun's interior to the surface. At times of great solar activity, therefore, we might expect increased radiation. But this might soon be checked by the diffusion through the solar atmosphere of materials thrown upward by the violent eruptions, which characterize such periods of activity. Indeed, the increased absorption, persisting after the subsidence of unusual activity, might result in a reduction of the radiation below its normal value.

Evidently a comparison must be made between observations of various kinds, carried on simultaneously. Spectroheliograph plates, bearing the record of the area covered by the flocculi, afford an index to the solar activity. The absorption of the solar atmosphere may also be measured by allowing the solar image to drift slowly across a bolometer, and photographing the galvanometer deflections upon a falling plate. During the summer of 1906 both of these classes of work were carried on at Mount Wilson, simultaneously with Abbot's measurements of the solar constant. When all the results are discussed together, new light may be thrown on the subject.

But the work is barely started, and must be continued for many years under the best conditions. Simultaneous observations at several widely separated mountain stations are greatly to be desired, to make certain that local changes in our own atmosphere are in no wise concerned in the apparent solar changes. Moreover, the work should go on without the interruptions caused by the rainy season. If, for example, a bolographic outfit were established at the Solar Observatory at Kodaikanal, in south India, at an elevation of 7,000 feet, the dry season there would correspond with the rainy season in southern California. An Australian station might also accomplish very important results. It is to be hoped that adequate provision may soon be made to carry out this important work.

But, it may be asked, must not such fluctuations of the solar radiation, if real, be the cause of marked changes of terrestrial temperature, easily detected and obvious in their effects? Abbot believes that the thermometric records do actually reflect these solar variations, but Newcomb holds the contrary view. It is evident that complex meteorological phenomena may be involved, and that their disentanglement may require long-continued research. For this reason the studies of the solar radiation undertaken by the International Union for Co-operation in Solar Research, the co-operation in meteorological work set on foot by the Solar Commission, and the labors of such an institution as the observatory recently established on Mount Weather, Virginia, by the United States Weather Bureau, should prove of value. In the exhaustive study of so important a problem the cordial co-operation of many investigators is essential to success.

CHAPTER XXIII

THE CONSTRUCTION OF A LARGE REFLECTING TELESCOPE

THE grinding and polishing of a 60-inch mirror involve a variety of operations, described in detail in Ritchey's memoir *On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors*,[1] the most authoritative treatise on the subject. A brief account of these operations, taken in large part from the above source, may be of interest here.

It is first necessary to obtain a suitable disk of glass. The disk (of plate glass) made by the French Plate Glass Works, of St. Gobain, France, for the reflecting telescope of the Solar Observatory is 60 inches in diameter, 8 inches thick, and weighs a ton. It must be remembered that the requirements for a large mirror are very different from those for a lens through which light is to pass. The mirror disk is merely a support for the thin silver film on its front surface, from which the light is reflected without entering the glass. For this reason the great perfection of a lens disk is not necessary. Nevertheless, the glass must be free from striae and other evidences of irregularity of structure. It should contain no large bubbles, though a few small ones, if they do not lie on the surface, are not objectionable. The most important condition, however, is freedom from strain caused by imperfect annealing. Evidences of strain are detected by a test with polarized light. Such a test, however, cannot be final, as an incident in the history of a great telescope objective illustrates. The disk had been carefully

[1] Published by the Smithsonian Institution.

annealed and was supposed to be suitable for its purpose. During the process of grinding it flew to pieces, on account of internal strain, the serious nature of which had not been recognized in the test with polarized light.

It may not be obvious why the disk must be so thick, when its sole purpose is to support the thin film of silver on its accurately figured face. Great thickness, however, is absolutely essential, to diminish the effects of bending due to the weight of the glass and to temperature changes. The thickness of a mirror should not be less than one-eighth or one-seventh of the diameter. Even with such thickness a special support system is necessary to prevent flexure.

Glass is chosen in preference to other materials for telescope mirrors because of its uniformity of structure, comparative ease of working, and capacity for a high polish. Its lightness, when compared with such substances as speculum metal (formerly employed for telescope mirrors), is an important advantage. Furthermore, a surface of pure silver, first used by Foucault, reflects a much larger proportion of light than polished speculum metal.

The grinding-machine, designed and constructed by Ritchey for his work on the 60-inch mirror, is shown in Plate XCII. The glass disk rests on a heavy cast-iron turn-table, carried by a vertical steel shaft. Between the lower surface of the glass (ground flat) and the turn-table are two thicknesses of Brussels carpet, which form an admirable support during the grinding and polishing process. The edge of the glass is ground true by means of a rapidly rotating iron face-plate, held against the disk while the turn-table is slowly rotated. The cutting material is powdered carborundum, carried down between the glass and the face-plate by a slow stream of water. After the edge-grinding is completed, the two faces of the glass are ground plane

and parallel, before the process of making one of these surfaces concave is undertaken.

The grinding-tools employed for this work are circular plates of cast-iron, strongly ribbed on the back, and divided into a series of small squares on the grinding surface, by two sets of parallel grooves, planed at right angles to one another. The tool rests on the surface of the glass, though in Plate XCIII it is shown suspended from the lever arm, employed to swing the heavy tools into or out of position. During the grinding the disk is slowly rotated and the tool, also kept in rotation, is moved over its surface in a series of strokes from four to eight inches in length, by means of the arm shown above the disk in Plate XCIII. On its right-hand extremity this arm terminates in a steel shaft, which moves back and forth through a swiveled bearing supported on an adjustable slide. In this way the position of the grinding-tool on the disk can be changed laterally, so as to bring the stroke across the center of the glass or near the edge. If it is found, for example, that the center is being cut away too rapidly, the tool is moved near the edge and the grinding continued there until the error is corrected. The tool is not kept at any one position for a great length of time, to avoid producing low zones in the glass.

For the grinding process, various grades of carborundum are prepared in the following way: The powdered carborundum is mixed with water and thoroughly stirred. After settling for two minutes the coarse particles reach the bottom of the bucket and the liquid, containing "two-minute" carborundum and the finer grades, is siphoned off into another bucket. After the contents of the second bucket have been allowed to stand four minutes, the liquid is poured off and the "two-minute" carborundum at the bottom of the bucket is set aside for fine grinding purposes. In the same way, carbo-

rundum which has remained in suspension for periods up to one hundred and twenty minutes, or even longer, is prepared, These very fine grinding materials are used to give the smooth and almost polished surface obtained after the grinding with coarser carborundum is completed.

A perfectly true Brown & Sharpe steel straight-edge is used to determine whether the surface of the glass is approximately plane. When it is found to be sufficiently so for the preliminary work, the fine grinding is commenced, beginning with two-minute carborundum and continuing with finer grades. In this work the iron grinding-tool is counter-poised by placing weights on a lever arm connected by a shaft with the tool. The pressure is reduced from one-third pound to the square inch for the five- or ten-minute carborundum, to about one-twelfth pound per square inch for the one-hundred-and-twenty- and two-hundred-and-forty-minute carborundum. Unless this precaution is taken there is great danger of scratching the glass.

After being fine ground, the back of the mirror is polished with rouge in the manner described later. No great pains are taken with this surface, although it is made very nearly plane, and is then polished so as to permit silvering (Plate XCIV). It is desirable to silver the back of the mirror, as well as the front, in order to prevent temperature changes from affecting the two surfaces in unequal degree.

The front surface, after it has been given a plane figure, is ready to be made concave. For this purpose a convex iron tool, of suitable curvature, is employed. In the case of the 60-inch mirror the radius of curvature is 50 feet. The curvature of the tool, and also of the glass, is tested from time to time by a spherometer. This consists of a tripod, with a micrometer screw at its center, which permits the deviation of the surface from a plane to be accurately determined. After the desired curvature has been secured, the

fine grinding is carried to a point where the surface is very smooth and ready for polishing.

The polishing and figuring are done by means of a tool built up of narrow strips of wood, saturated with paraffine to prevent change of figure. The face of this tool is covered with squares of rosin, of a certain degree of hardness, which can be determined only by experience. The rosin squares are finally coated with a thin layer of beeswax, which forms the polishing surface. The soft wax is very useful, since small hard particles that may happen to be present in the polishing material are likely to bed themselves in it, thus reducing the danger of scratches. As a preliminary to polishing, the tool is placed in contact with the glass disk and pressed against it, by weights placed on the back, so that it may acquire the same curvature as the surface. After pressing for some hours, until the waxed squares appear smooth and bright in all parts, the polishing may begin. This is accomplished by moving the tool over the rotating glass, by the main arm of the machine, as in the case of the grinding process. The polishing material is powdered jewelers' rouge, used commercially for polishing plate glass. The fine rouge is separated from impurities and coarser particles by a washing process similar to that used for carborundum. The rouge, mixed with distilled water, is applied to the surface of the glass by means of a wide brush of cheese-cloth.

The greatest precautions must be taken throughout the polishing process to avoid scratches. For this purpose the room in which the work is done is fitted up in such a way as to eliminate danger from dust. In the polishing-rooms of the Solar Observatory optical shop (Plate XCV) the plastered walls and ceilings are heavily varnished, and a canvas screen is hung above the glass, to protect it from any falling particles. The cement floor is painted, and kept wet when the

polishing is in progress. The windows are double and carefully sealed, outer air being admitted to the room through a cheese-cloth filter. The temperature is maintained constant, within two or three degrees, by means of a hot-water furnace, controlled by a thermostat. The motor, driving-shaft, and apparatus for varying the speed of the grinding-machine, are carefully inclosed, only the slow-moving belt coming out into the room. No one is permitted to enter the room except the optician, who wears a surgeon's gown and cap. By observing such precautions the work may be continued for months without producing even microscopic scratches in the glass surface.

We may now assume that the glass has been polished, after receiving an approximately spherical surface. It then becomes necessary to apply a more accurate test than the spherometer permits. For this purpose the glass is turned into a nearly vertical position, where it is supported by a steel edge-band (Plate XCV). An artificial star, consisting of a hole about $\frac{1}{300}$ of an inch in diameter illuminated by an acetylene lamp or other brilliant source of light, is placed at the center of curvature, 50 feet from the glass surface. The light from the articifial star then falls upon the disk and is reflected back so as to form an image close beside the pin-hole. If the surface is perfectly spherical, it will appear, when examined by the eye placed at this point, to be brilliantly and uniformly illuminated. With an eye-piece, the image of the pin-hole will then be perfectly sharp, showing the most minute details or irregularities of the hole itself.

It is much more probable, however, that the surface will have many zonal errors. To detect and interpret these, the "knife-edge test," due to Foucault, is employed. If all the zones come to a focus at the same point, and a knife edge is moved across this point, while looking at the glass, the light will be cut off instantly from all parts of the disk. If, how-

ever, the curvature of certain zones is greater or less than the average curvature, these zones will resemble projecting or receding rings on an otherwise uniformly bright surface. The effect is as though the light were shining from one side, producing an appearance of relief by lights and shadows. The test is so sensitive that an error of $\frac{1}{500000}$ part of an inch can be detected. If, for example, the finger is placed for a few moments on the glass, the heating of the surface will cause a swelling easily to be detected by the knife-edge test.

The process of figuring consists in removing the high and low zones by means of the polishing tool, the stroke and position of which must be modified in accordance with the results of the knife-edge test. After a perfectly spherical form has been obtained in this way, the difficult process of changing the spherical to a paraboloidal surface is begun. As is well known, the parallel rays from a star, falling on a spherical surface, will not be brought to a focus at a central point, but in an irregular figure, called a "caustic." A paraboloid, however, brings all parallel rays to a single focus, and produces a perfect stellar image. In the case of the 60-inch mirror, which has a focal length of 25 feet, the paraboloid is deeper than the sphere at the center of the disk by a quantity less than $\frac{2}{1000}$ of an inch. Months of figuring are required, however, to produce this small difference, because of the necessity of giving each zone of the paraboloid precisely the right curvature. In testing the surface from the center of curvature, the measured radius of each narrow zone of the mirror (the other parts being covered by a cardboard screen) must correspond with the calculated radius. The extreme difficulty of accomplishing this may be appreciated when it is remembered that the deviation of any zone from the surface of a perfect paraboloid must not be greater than $\frac{2}{1000000}$ of an inch, which

would correspond to a change of $\frac{1}{100}$ of an inch in the radius of curvature.

When parallel light is available, the difficulties of securing a perfectly satisfactory test of a paraboloidal mirror are greatly reduced. In this case the mirror, when seen from its focal plane (25 feet from the glass, or one-half the radius of curvature) appears like a uniformly illuminated plane surface when a perfectly paraboloidal form has been obtained. This method of testing with parallel light has been developed by Ritchey, and was used by him to secure the last degree of perfection in the figure of the 60-inch mirror.

As already explained, the problem of mounting a large mirror is quite as serious as that of figuring it. It is necessary, in the first place, to support the mirror in such a way that it will retain its form, without bending, in any position of the telescope. Furthermore, it must be held so that it will not slip laterally, since the slightest change in the position of the mirror with respect to the tube will cause a displacement of the star images on the photographic plate. The mirror, thus supported, must be carried at the lower end of a tube, of skeleton construction, open at the top, and so mounted that it can be pointed toward any part of the heavens and made to follow the apparent motion of the stars by rotation about an axis parallel to the axis of the Earth. Strength and stability of the mounting, freedom from flexure, perfection of optical and mechanical construction and adjustment, and the greatest precision of driving—all these conditions must be met before a large reflector can be expected to give satisfactory results, in the more exacting departments of photographic work.

The difficulties thus presented have been most successfully solved by Ritchey, whose design for the mounting of the 60-inch mirror is shown in Plate XCVI. The telescope tube

is hung between the arms of a massive cast-iron fork, which is bolted to the upper end of the polar axis. This axis, a hollow forging of nickel steel, is inclined at an angle corresponding to the latitude of Mount Wilson (34° 13′) and thus rendered parallel to the axis of the Earth. Leveling screws, by which the base of the mounting is supported on its pier, permit this adjustment to be made with great precision. In order to relieve the great friction of this axis on the upper and lower bearings in which it lies, a hollow steel float, 10 feet in diameter, is bolted to its upper end, just below the fork. This float dips into a tank filled with mercury. Thus the entire instrument is floated by the mercury, and in this way the friction on the bearings is reduced to a minimum.

The 60-inch mirror rests at the lower end of the tube, on a support system consisting of a large number of weighted levers, which press against the back of the glass and distribute the load. A similar series of weighted levers around the circumference of the mirror provide the edge support. The path of the rays from the star may be as shown in Plate XCVII, Figs. 1, 2, 3, or 4. In the first arrangement (the Newtonian telescope), the parallel rays, after striking the mirror, are reflected back and would come to a focus at a point just beyond the end of the tube. They are intercepted, however, by a plane mirror of silvered glass, which turns them at right angles and forms the image on the photographic plate, which is mounted on the side of the tube near the upper end. In this case the focal length of the instrument is 25 feet, and the image is formed without secondary magnification.

If, however, it is desired to secure, for certain classes of work, the advantages of a greater focal length, a different arrangement is adopted. The upper section of the tube, bearing the plane mirror, is removed, and a shorter section

substituted for it. This carries a hyperboloidal mirror, which returns the rays toward the center of the large mirror and causes them to converge less rapidly. They then meet a small plane mirror, supported at the middle of the tube near its lower end, which sends them to one of the following instruments, mounted in the focal plane: (1) a double-slide plate-holder, carrying a sensitive plate, for the photography of the Moon, planets, bright nebulae, etc., with an equivalent focal length of 100 feet (Fig. 3); (2) a spectrograph mounted in place of this photographic plate, in which case a convex mirror of different curvature is employed, and the equivalent focal length is 80 feet (Fig. 4); or finally (3) a third convex mirror may be used and the plane mirror inclined so as to form the star image (after sending the light down through the hollow polar axis) on the slit of a powerful spectrograph, of 13 feet focal length, mounted on a pier in a constant-temperature chamber (Fig. 2). In this case the equivalent focal length is 150 feet.

The telescope is moved in right ascension or declination by electric motors, controlled from the floor of the observing-room. The driving-clock moves the telescope in right ascension by means of a worm-gear, 10 feet in diameter, carried by the polar axis. The cutting of the teeth of this worm-gear is a mechanical operation requiring the highest precision of workmanship. Each tooth was spaced off by means of a finely divided circle attached to the polar axis, and read with a microscope. The rotating cutter was driven by an electric motor. After all the teeth had been cut, the worm and worm-gear were ground together for many hours, until all slight residual errors had been eliminated. The operation was completed with jewelers' rouge, which leaves a smooth and highly polished surface.

All of the heavy parts of this mounting were made, after Ritchey's designs, by the Union Iron Works Company, of

San Francisco. They were then shipped to Pasadena, where the mounting has been erected in the Solar Observatory shop (Plate XCVIII). Here the worm-gear was cut, and all of the smaller parts, including the driving-clock, setting-circles, slow motions, motors, etc., are being fitted and adjusted. All of these parts were made in the Observatory instrument shop, which is equipped with the best machinery obtainable for work of this kind (Plate XCIX).

As soon as this mounting has been completed, the 60-inch mirror will be put in place and the telescope thoroughly tested, by actual photography of the heavens. It will then be necessary to transport the instrument to Mount Wilson—an operation of considerable difficulty, as several of the castings are very large, and weigh about five tons each.

The building for the 60-inch reflector is of steel construction throughout (Plate C). The thin inner walls will be shielded from the Sun by outer walls, and air will be permitted to circulate in the space between the two. The dome, 60 feet in diameter, will be rotated by an electric motor, either rapidly, when passing from one part of the heavens to another, or at a slow, uniform rate, of such a speed as to keep the opening (15 feet wide) constantly opposite the end of the telescope tube, when it is following a star. The observer, when photographing in the principal focus, will stand on a platform suspended from the dome and rotating with it. The double-slide plate-carrier, with which stars and nebulae will be photographed, is similar to that used with the Yerkes telescope (Plate XVII).

CHAPTER XXIV

SOME POSSIBILITIES OF NEW INSTRUMENTS

In looking toward the future and endeavoring to imagine what appliances will be employed by the astronomer of the next generation, the line of least resistance is to consider the possibilities of improving existing telescopes and the auxiliary apparatus employed with them; for the prevision of more radical departures is beyond our province. It is safe to predict that the equatorial refractor, of which the Lick and Yerkes telescopes are types, will hold an important place in observatories for many years to come. The ease with which such instruments can be pointed toward any part of the heavens; the absence of reflecting surfaces; the permanence of object-glasses, as contrasted with the necessity of silvering mirrors from time to time; the convenient position of the observer at the lower end of the tube, rather than at the upper end of a Newtonian reflector: these and other considerations point to the long-continued use of the standard refractor. In its most perfect form this instrument is still capable of some improvements, the most important of which will be the introduction of truly achromatic object-glasses, capable of uniting the rays of all colors at the same focus.

It seems probable that the uses of the equatorial refractor will be confined more and more to visual observations, and to certain departments of photography, especially those involving great precision of measurement or the inclusion of large fields on a single plate. For the latter work the refracting telescope, particularly in the portrait-lens form, possesses great advantages, on account of the very limited field of the reflector. It does not at present appear desir-

able to increase the aperture of refractors beyond the limit of 40 inches reached in the Yerkes telescope. The resolving power of such an aperture, when the atmospheric conditions are good enough to permit its realization, is sufficiently great for the most exacting demands of visual work. Increased light-gathering power, which is much to be desired for the investigation of faint objects, will be most easily and effectively obtained through the use of large reflecting telescopes. Increased focal length, on the other hand, which is needed to give larger solar images, can best be secured through the use of some form of fixed telescope. We may now consider what types of telescopes are likely to prove most serviceable in photographic and spectroscopic studies of the Sun, stars, and nebulae.

Many important investigations require the use of a telescope giving a sharply defined solar image, of large diameter, at a fixed position within a laboratory. The focal length of such a telescope must not change rapidly when the instrument is exposed to the Sun. The image must not rotate, and the laboratory conditions must permit the successful use of the largest and most powerful spectrographs and spectroheliographs. The Snow telescope meets most of these requirements in a very satisfactory manner. The one difficulty with this instrument is the distortion of the image and the change of focus when the mirrors are exposed for some time to the Sun. When the precautions described in chap. xv are taken, these obstacles are easily overcome in current work with the 5-foot spectroheliograph and the Littrow spectrograph. But with long exposures, such as are required with a spectroheliograph of very high dispersion, the change of focus during the exposure would be a serious obstacle. It is probable that by substituting very thick mirrors for those now used in the Snow telescope, and by reflecting sunlight upon their rear surfaces, which should be silvered like the

front surfaces, the tendency to distortion could be overcome. For a very thick mirror would resist the bending which results from the expansion of the front surface; and even if the figure were changed, the compensating effect produced by heating the rear surface should restore it. But the Snow telescope is fully occupied with its present work, for which it is well adapted. Accordingly, a new type of fixed telescope has been devised for the purpose of supplementing the Snow telescope, particularly in photographic work involving long exposures.

In the new instrument the coelostat, provided with mirrors a foot thick, will be mounted at the summit of a steel tower 65 feet in height (Fig. 7). From the second mirror the sunlight will be sent vertically downward to a 12-inch object-glass, mounted a short distance below it. This object-glass, of 60 feet focal length, will form an image of the Sun near the ground level. The new instrument will thus consist essentially of a fixed refracting telescope, pointing directly to the zenith and receiving light from a coelostat and second mirror.

The spectroscopic laboratory at the base of the tower will be excavated in the earth, to insure constancy of temperature and great stability of the instruments it will contain. Of these, the one shown on the left in Fig. 7[1] is a Littrow spectrograph, similar to the one employed with the Snow telescope, but of much greater power. This instrument will have a focal length of 30 feet, and be provided with a large plane grating. On the right is shown a spectroheliograph of 30 feet focal length, designed for extending the monochromatic photography of the Sun to many of the finer lines of the spectrum (p. 236). The atmospheric calm that prevails on

[1] This is only a general diagram, omitting all details, such as the steel house, at the base of the tower, which covers the upper ends of the spectroscope and spectroheliograph; the small electric elevator, to convey the observer from the bottom of the underground laboratory to the summit of the tower, etc.

Mount Wilson during the best observing season may permit the inner tower to be used merely as a skeleton, if firmly stayed in position by strong steel guy-ropes. If, on experiment, it is found that the wind produces too much vibration of the structure, an outer tower, covered with canvas louvers,[1] will be erected to shield the inner one, as indicated in Fig. 7.

It remains to be seen whether this type of telescope will meet the rigorous conditions demanded in the case of a fixed instrument for solar research. The vertical beam of light should be less affected by unequal temperature conditions than a horizontal beam, and the considerable height of the coelostat and object-glass above the ground may also prove advantageous. Should it prove successful, a similar instrument of larger aperture, and of about 150 feet focal length, may ultimately be constructed, on account of the importance of providing a very large image of the Sun for certain classes of spectroscopic and spectroheliographic work. It is probable enough that some other type of fixed telescope would be better than this, but the results of our experience up to the present time give reason for the belief that the present design will prove satisfactory.

Since the principal difficulty to be overcome in the construction of a fixed telescope for solar work is the distortion of the mirrors by the Sun's heat, it is to be hoped that homogeneous disks of fused quartz can ultimately be employed for mirrors, in place of glass. The coefficient of expansion of fused quartz is only about one-tenth that of glass, and hence it is but slightly subject to change of figure by heat. Many small quartz disks have been made in an electric furnace at the Solar Observatory, but the presence of numerous bubbles, which cannot be removed from the very viscous fluid by stirring, have proved an insuperable obstacle to the use

[1] Or perhaps with fine wire netting, which should break the wind, and yet not heat sufficiently in sunlight to produce convection currents.

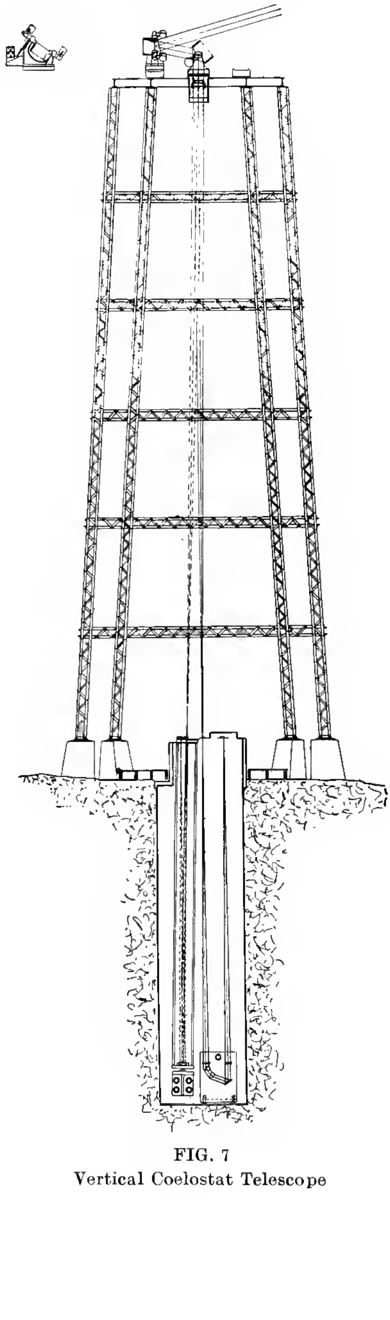


FIG. 7
Vertical Coelostat Telescope

of these disks for optical purposes. Day has met with better success in the geophysical laboratory of the Carnegie Institution, where an electric furnace of special type permitted quartz to be fused under pressure. His results are sufficiently promising to lead to the hope that, if a large furnace, of suitable design, were constructed, disks of 15 to 20 inches in diameter might be made. In view of the expense of such a furnace, it has seemed best to defer further experiments in this direction until very thick glass mirrors can be thoroughly tested.[1]

Another important need of the future is a machine capable of ruling gratings of much larger dimensions than those of Rowland. The best Rowland gratings, which have rendered possible the great advances of the last quarter-century in spectroscopy, have a ruled surface about $5\frac{1}{2}$ inches long. The resolving power of a grating depends upon the total number of lines it contains, but there are many reasons why it is not desirable that the number should exceed 20,000 per inch. If a good 15- or 20-inch grating could be ruled, with lines from 10 to 15 inches in length, a great advance in solar spectroscopy would be rendered possible. Such a grating, if one of the spectra were very brilliant, would be exactly what is required for a spectroheliograph capable of photographing the Sun through narrow dark lines. If used in a spectrograph of from 40 to 50 feet focal length, it would furnish a photographic map of the solar spectrum much superior to Rowland's, and be of the greatest service in the photography of sun-spot spectra, the study of the solar rotation, and many other investigations. For this purpose the spectra of one of the higher orders (from second to fourth) should be bright, and the precision of ruling

[1] Since the above was written the "tower telescope" has been constructed and tested. The thick mirrors are so little affected by sunlight that the focus will remain constant during the long exposures required with the 30-foot spectroheliograph (Plates CI and CII).

should, of course, be so high as to permit the theoretical resolving power to be attained. In view of Michelson's recent work in ruling 8-inch and 10-inch gratings, the realization of his plan for the construction of a machine capable of making gratings of much larger size is more earnestly to be desired than that of any other project for the development of spectroscopy.

Still another important need of the spectroscopist is homogeneous glass, in large masses, for prisms. At the present time it is almost impossible to obtain prisms of large size that will give good definition. The repeated failures of the best makers of optical glass indicate that the problem is not an easy one, though it can probably be solved. A careful study of this question, made with special reference to the possibility of improving the present methods of annealing, should yield valuable results. Large prisms are urgently required for use in stellar spectrographs of large aperture and high dispersion, such as the one which is to be mounted in a constant-temperature chamber in conjunction with the 60-inch reflector. However, if sufficiently large and perfect gratings can be obtained, which concentrate nearly all of the light in a single spectrum. they may be better for this purpose than prisms.

In the further development of solar research, no instrument seems to offer more possibilities than the spectroheliograph. Recent experiments with a temporary spectroheliograph of 30 feet focal length, used in conjunction with the Snow telescope, have demonstrated the feasibility of photographing sun-spots with the lines that are strengthened or weakened in their spectra. The resulting pictures show the distribution of the corresponding vapors in and around the spots, and should be capable of throwing much new light on solar phenomena when taken daily and systematically studied. It is expected that the 30-foot spectroheliograph

of the "tower telescope" will be employed in this way, but even the great dispersion of this instrument will be inadequate for work with the finest lines. It is evident that if the photograph is to represent the distribution of the gas or vapor corresponding to the line employed, the line must be as wide as the second slit, in order that light from the adjoining continuous spectrum may not obliterate or confuse the image produced by it. When it is remembered that the solar spectrum contains more than 20,000 lines, and that any one of these may be capable of furnishing a photograph comparable in interest with the results already obtained with hydrogen and calcium lines, it will be appreciated that no effort should be spared to increase the dispersion and optical perfection of the spectroheliograph. The further applications of this instrument to the study of the level of the flocculi; the absorption of the solar atmosphere; the growth of the flocculi and prominences, which can be shown, as if in accelerated progress, by the aid of a series of pictures taken in rapid succession and projected on a screen with a kinematograph; the use of stereoscopic methods in spectroheliographic work: these, and many other investigations, leave no doubt that this field of solar research is but barely opened, and still contains many untried possibilities.

Passing over other considerations that tend to confirm one's optimistic belief in the future of solar research, we may now inquire as to the type of telescope that appears most promising for photographic and spectrographic studies of stars and nebulae. In much of this work it is not essential, as in the case of the Sun, that the image should be fixed in a laboratory. For this reason, an equatorially mounted reflecting telescope seems to meet the requirements admirably. Even when a fixed image is required, it is possible, as illustrated in Fig. 2, Plate XCVII, to send the light from objects lying within a certain zone of the heavens into a constant-

temperature laboratory, for analysis by the most powerful spectrographs. As already explained, such a telescope is also adapted for many other classes of work, either in the principal focus of the great mirror or with an enlarged image given by a convex mirror, after the manner of Cassegrain.

As an object-glass increases in size, the absorption, due to its increased thickness, rapidly diminishes the percentage of light it transmits. The loss is especially serious for the blue and violet rays, since these are absorbed more completely than the red and yellow. In the case of a mirror, the light passes through no glass, but falls on a surface of pure silver, from which it is reflected to the focal plane. Thus every square inch added to the area of a telescope mirror means a proportional increase in the light-gathering power. It is evident that if the mechanical and optical difficulties can be overcome, reflecting telescopes much more powerful than any now in existence can advantageously be constructed.

With this object in view, Mr. John D. Hooker has presented to the Carnegie Institution a sum sufficient to purchase for the Solar Observatory a glass disk 100 inches in diameter and 13 inches thick, and to meet other expenses incident to the construction of a 100-inch mirror for a reflecting telescope of 50 feet focal length. The construction of a telescope so far surpassing all previous instruments in size must, of course, be partly in the nature of an experiment. The immense block of glass will weigh $4\frac{1}{2}$ tons, four and one-half times as much as the disk of the 60-inch mirror. The difficulty of providing a mounting capable of carrying it with the necessary precision is not slight. The glass is certain to be more or less distorted by temperature changes, which would ruin its performance if not obviated. The atmospheric conditions, even on Mount Wilson, may not be sufficiently

good to permit so great an aperture to be used to full advantage. Of these and other obstacles Mr. Hooker is fully informed, and he does not underestimate their importance. But he perceives and appreciates, with the understanding of one who has himself invented and developed mechanical appliances, that experiment is necessary to progress. He therefore does not hesitate to provide the means for undertaking an optical experiment on a large scale. Let us consider its probable outcome.

In the first place, the question arises whether a sufficiently homogeneous glass disk of the required dimensions can be obtained. Our long experience with the Plate Glass Company of St. Gobain (France) leads us to believe that no insuperable difficulty will be encountered. This old and reliable company has cast for us scores of disks, from which Ritchey has made many plane and concave mirrors, from the smallest sizes up to 60 inches. In all of these cases the quality of the disks has left nothing to be desired. The 60-inch, 8 inches thick, and weighing a ton, is fully equal to the smaller ones. We are therefore inclined to believe, since the St. Gobain Company expresses its deliberate opinion that a satisfactory disk, 100 inches in diameter and 13 inches thick, can be produced, that they will be able to carry out the order we have given them.

As for the work of grinding and figuring, no one who has watched the progress of the 60-inch mirror would be likely to doubt Ritchey's ability to accomplish this difficult task. The method of parabolizing which he has perfected will apply as well to a 100-inch mirror as to the 60-inch. It eliminates the necessity of handwork, except for a few finishing touches, and has yielded an essentially perfect paraboloidal figure in the case of the 60-inch mirror. I am confident that he will find no difficulty in bringing the 100-inch mirror to this highest order of perfection.

The mounting should offer no great obstacles, especially as it will not be built until the mounting of the 60-inch has been thoroughly tested on Mount Wilson. In these days of large and perfect machinery, the mechanical difficulties are much less formidable than they would have appeared twenty years ago. On this score, therefore, we see no cause for fear.

The prevention of change of figure due to changing temperature should not prove a very serious problem. During the fine nights of the best observing season on Mount Wilson the temperature remains almost perfectly constant after 9 P. M. It will therefore only be necessary to maintain the mirror (or possibly the entire telescope) at approximately this temperature throughout the day, by means of suitable refrigerating machinery. In the long periods of cloudless weather the change of temperature from night to night is extremely small, so that little difficulty should be encountered on this score. If the slowly falling temperature during the early evening should prove to give trouble, the observational work may be deferred until after nine o'clock. The dome and building, like those for the 60-inch reflector, will be so constructed that no air can enter during the day; they will also be shielded from the heat of the Sun. The problem is, of course, altogether different from that encountered in the case of the Snow telescope, where the mirrors are required to give good images in spite of their exposure to direct sunlight.

Assuming that these various difficulties can be successfully overcome, it still remains a question whether the atmospheric conditions on Mount Wilson will be sufficiently good to permit the telescope to give satisfactory images. This cannot be definitely determined until after the 60-inch reflector has been used for some time. Even if it should prove, however, that only a very few nights in the course of a year can

be utilized to the fullest advantage, the construction of such a telescope would nevertheless be desirable. For under the average summer conditions, which are much finer than those in the eastern part of the United States, results of great value can undoubtedly be obtained in many classes of work, such as the photography of stellar spectra, the measurement of the heat radiation of the stars, etc. The immense amount of light which this mirror will collect should render it particularly suitable for spectroscopic work of all kinds.

It need hardly be said that the 100-inch mirror, when suitably mounted, will play a most important part in the scheme of research of the Solar Observatory. The investigation of stellar evolution frequently calls for adequate spectroscopic study of stars beyond the reach of existing instruments. With the 40-inch Yerkes telescope, for example, it was impossible to obtain satisfactory evidence, positive or negative, as to the transition from solar stars to those of the fourth type. The large number of stars within the reach of a 100-inch reflector (which will give images about ten times as bright as the 40-inch) should greatly increase the chances of finding possible intermediate types, so important in their bearing upon the relationship of solar and red stars. This is only a single instance, but it forcibly suggests itself when considering our programme of research. In other fields the large reflector should be equally valuable, especially for the photography of the numerous small spiral nebulae, the details of which should be brought out to good advantage with a focal length of 50 feet; minute investigation of the larger nebulae, in the hope of detecting changes in their form; the study, with very high dispersion, of the spectra of bright stars, etc. The remarkable calm of the summer nights on Mount Wilson should assist materially in all of this work, since vibration of the tube, caused by the wind, would undoubtedly be a serious drawback under less favorable conditions.

It is impossible to predict the dimensions that reflectors will ultimately attain. Atmospheric disturbances, rather than mechanical or optical difficulties, seem most likely to stand in the way. But perhaps even these, by some process now unknown, may at last be swept aside. If so, the astronomer will secure results far surpassing his present expectations.

CHAPTER XXV

OPPORTUNITIES FOR AMATEUR OBSERVERS

I SHALL never forget my delight, when as a boy, I first learned of the spectroscope. Its extraordinary achievements, and the endless possibilities, vaguely imagined, of its further applications in astronomical research, filled me with enthusiasm, and kindled a strong desire for immediate work. The visual study of flames, with a simple one-prism spectroscope, aroused an ambition to photograph spectra. This was soon accomplished, by substituting an ordinary camera for the observing telescope. But the scale of the photographs was too small, so I built a longer camera of wood. Later, when Rowland was making his earliest gratings, one of the smallest size was secured, and substituted for the prism. The marvelous increase in resolving power, and the greatly augmented beauty of the solar spectrum, led to observations of the solar prominences, and subsequently to more serious research. But none of the pleasures of later years, during which I have enjoyed the privilege of using larger and more powerful instruments, has surpassed the delight of the initial work, much of which was done with simple and inexpensive apparatus of my own construction.

These remarks are called forth by certain criticisms I have heard of great modern observatories. Some amateurs, I am told, believe that their efforts are rendered futile by the more powerful equipment and better atmospheric advantages of other investigators. If this feeling were well-grounded, it might fairly be asked whether the great observatories are worth their cost. For the history of astronomy teaches that much of the pioneer work has been done by

amateurs, usually with modest means and in unfavorable climates. To discourage this class of workers, unfettered as they are by the traditions of institutions, and driven by their own initiative into unexplored fields, would be a serious error, hardly to be atoned for by any services the larger observatories can render.

We may therefore inquire whether useful work, of such a nature as to contribute in important degree to the progress of science, can still be done with simple and inexpensive instruments. This question may at once be answered in the affirmative. The results of amateur observations may not only be useful—they may equal, or even surpass, the best products of the largest institutions. Great care must be exercised in choosing the subject of research, in constructing the instruments, in making the observations by the best methods and at the most favorable hours, and in the reduction and discussion of the results. If such precautions are observed, discouragement will soon give way to confidence and success.

Take, for example, the direct photography of the Sun. A 2-inch objective, of 40-feet focal length, will give beautiful solar photographs, over 4 inches in diameter, perfectly adapted for the study of the solar rotation, the proper motions of the spots, and other important purposes. Details separated by less than two seconds of arc will not be resolved on these photographs, but in many classes of work little gain would result from increased resolving power. Such an objective should be mounted so as to send the beam horizontally (better vertically) across shaded ground, or within a building, to the photographic plate. If no coelostat is available, a small mirror, with optically plane reflecting surface, will serve the needs of direct photography. It is only necessary to mount it on a wooden support, so that it can be held at the angle required to reflect sunlight through the objective. The exposures—made by the rapid motion of a wooden shutter, pierced by a

narrow slit with brass edges, mounted just in front of the plate—are very short, and the slight drift of the solar image during this time can be overcome, when desired, by a very simple driving mechanism. Between exposures the small mirror should be shielded from the Sun. The apparatus used by the American parties to photograph the last transit of *Venus* across the Sun was of this type, except that a 4-inch objective and larger mirror were used.

It will probably be found that the best solar definition occurs in the early morning, before the ground is greatly heated. A careful study should be made of the local conditions before selecting the hours of work.

Solar photographs, made in this way at intervals of from one to several hours, may be combined in the stereoscope with striking results. More important, however, would be a long series of photographs, made at short intervals, and examined with a kinetoscope. These should show the Sun rotating under one's eyes, the spots near the equator moving more rapidly than those in higher latitudes. The effect of proper motion, in causing some spots to overtake others in the same latitude, should also be very finely brought out. Even more interesting, however, would be the changing forms of spots, and the manner of their growth and decay, which have never yet been observed by this method.

The same horizontal telescope, with some modifications, would give an admirable image for spectroscopic work. The objective should, if possible, be of from 4 to 6 inches aperture, and from 40 to 60 feet focal length. The mirror should also be increased in the same ratio, and mounted as a coelostat, with its plane parallel to the Earth's axis. If the mirror is very thick—3 inches or more—its form will be changed but little by sunlight. A second mirror will be needed to send the beam to the spectrograph, as in the Snow telescope (Plate LVIII). If this arrangement appears formidable, it

should be remembered that almost all the parts can be made of hard wood, thoroughly soaked in melted paraffine, to prevent warping. The bearings are practically the only parts that need be of metal. A cheap clock movement, with heavy spring, will serve for a driving-clock, or a small electric motor may be used. With moderate ingenuity, any amateur accustomed to the use of tools can build such an instrument for a very small sum.

The spectrograph is even more simple. It should be of the Littrow form (p. 153), and the aperture of the single plano-convex lens that serves for both collimator and camera should be from 1 to $1\frac{1}{2}$ inches. Its focal length will be determined by the diameter and focal length of the objective used to form the solar image on the slit. If these are 4 inches and 60 feet, respectively, the ratio will be 1:180. Hence the focal length of the spectrograph lens should be 180 times its aperture, or from 15 feet to 22 feet 6 inches. The grating should be a 2-inch Rowland, or, if this is too expensive, a good replica by Ives, Wallace, or Thorpe. The replicas have the disadvantage of being made on transparent films, for use with transmitted light; but they can perhaps be converted into reflecting gratings by silvering.

The collimator-camera lens should be mounted on a vertical wooden bracket, arranged to slide 3 or 4 inches for focusing. The grating may also have a wooden support, consisting of a bracket, which can be tipped forward or back, mounted on a circular wooden table, permitting rotation about a vertical axis in the plane of the grating. Such rotation is necessary in order to bring different spectra upon the photographic plate, or to pass from one region to another in the same spectrum. The height of the spectrum on the plate can be adjusted by tipping the grating forward or back. It is also necessary to make the lines of the grating parallel to the slit; this can easily be done by hanging the bracket

from above, and defining its position by two side screws, passing through wooden blocks attached to the circular table. Plate CIII shows a wooden lens and grating support in regular use as part of a Littrow spectrograph of 18 feet focal length in the laboratory of the Solar Observatory.

The extreme simplicity of the slit end of the same instrument is illustrated by Plate CIV. A short slit, with one jaw movable by a screw, is supported by a tube fitting tightly in a hole bored through a wooden bracket. Below is the plate-holder, held in a frame that slides up and down, permitting many narrow spectra to be photographed on the same plate. In another similar instrument the slit and plate-holder support stands on a pier, and fits into a partition, so as to exclude all light from the room except that which enters through the slit.[1] In this case no tube is necessary between the plate and lens. The latter is mounted, with the grating, on a pier at a distance from the slit equal to the focal length of the lens.

In spite of the simplicity and cheapness of such a spectrograph, no better instrument could be asked. Its one drawback—the reflections of the slit from the surfaces of the lens—is easily removed by placing a bar across the lens (as shown in Plate CIV). Wooden spectrographs are in constant use at the Solar Observatory, and give results which are very satisfactory.

Any of the solar spectroscopic work described in this book can be done with such an instrument. The resolving power, even with only an inch aperture, will be sufficient for the separation of very close solar lines. The spectra of sun-spots, the solar rotation, the remarkable differences between the spectra of the center and limb of the Sun, and many other phenomena can be studied by its aid with the greatest precision and success. The exposures, it is true, must be longer than with

[1] This room is part of a long hall, for testing optical mirrors, in the Pasadena shop of the Solar Observatory. By opening large light-tight doors, the hall can be used for the transmission of light in the knife-edge tests.

a spectrograph of larger aperture, but this is not a serious obstacle. Indeed, it may be said that at the present time only two or three observatories in the world are using equipment as powerful as this for the classes of solar work just enumerated.

I might go on to describe a wooden spectroheliograph, fitted up with spare lenses and prisms, which gave excellent results with the Snow telescope before the 5-foot spectroheliograph was completed. Indeed, the photographs were quite equal to those taken with the latter instrument, except that they did not include the entire solar image, which is unnecessary for many kinds of work. The small coelostat telescope described above would give as good results as the Snow telescope with such a spectroheliograph, except that the exposures would be longer. The entire apparatus is easily within the reach of any intelligent amateur of limited means.

Those who desire to undertake solar work would do well to procure the *Transactions of the International Union for Co-operation in Solar Research*.[1] The aim of the Union is to encourage co-operation among observers, in the various fields where this is desirable. For example, it is impossible, in visual observations of sun-spot spectra, for one person to make a thorough study of more than a limited region. By mutual agreement, the spectrum is therefore divided up among many observers, who record their results on a common plan. Spectroheliographs, distributed from India across Europe to California, are also operated in harmony, and co-operation is practiced in other fields as well. Apart from such routine, however, every observer is encouraged to act on his own initiative, for the Solar Union recognizes that the greatest advances will come from individual effort, which no amount of co-operation can replace.

[1] Vol. I was published by the University Press, of Manchester, England, in 1906. Vol. II will soon appear.

INDEX

ABBOT: tests of Mount Wilson atmosphere, 129; solar radiation, 214; pyrheliometer, 215.

ABSORPTION: spectrum, 52; in solar atmosphere, 53, 68; in hydrogen flocculi, 96; in stellar atmospheres, 173.

ADAMS: metallic and spot spectra, 159; titanium oxide in spots, 162; spectrum of *Arcturus*, 168; spectrum of *α Orionis*, 170; Trapezium stars, 189; "*Orion*" type stars, 190.

ALTITUDES: advantages of high, 111–20.

AMATEURS: opportunities for, 27, 243–49.

Andromeda nebula, 41, 44.

ANOMALOUS DISPERSION and solar phenomena, 148.

Antares, 195.

Arcturus: spectrum, 168; heat radiation, 172, 173.

ASTROPHYSICS: relation to astronomy and physics, 6.

ATMOSPHERE: absorption in Earth's, 63, 114, 128; unsteadiness, 111, 112, 127.

BARNARD: photography of Milky Way, 30–33, 128; micrometric observations, 103; comparative photographs at Mount Wilson and Lake Geneva, 128, 129; tests of Mount Wilson definition, 129.

BARNARD AND RITCHEY: photography of corona, 76.

Betelgeuze: spectrum, 170.

BINARIES: spectroscopic, 105.

BOLOMETER, 215.

BOYS: stellar heat, 171.

BRUCE SPECTROGRAPH, 104, 167.

BRUCE TELESCOPE, 29–33.

BURNHAM: discoveries with small telescope, 27; observations with Yerkes refractor, 103.

CALCIUM: lines, H and K, 84, 91; flocculi, 85–93, 143, 147; vapor, radial motion of, 92.

CALCIUM HYDRIDE: in sun-spots, 163.

CALVERT: corona, 73.

CAMERA LENS: stellar photography with, 28–32.

CAMPBELL: stellar motions, 105.

Canes Venatici: spiral nebula in, 38, 39.

CARBON: in chromosphere, 80; in red stars, 195.

CARNEGIE, ANDREW: establishment of Carnegie Institution, 109.

CARNEGIE INSTITUTION: purpose of, 109.

CHAMBERLIN: criticisms of nebular hypothesis, 182–86; planetesimal hypothesis, 208–10.

CHROMOSPHERE, 15, 84; spectrum, 78; "flash" spectrum, 80.

COELOSTAT, 75, 109, 245; advantages, 131; Snow telescope, 133, 134; "tower" telescope, 231.

CO-OPERATION in research, 98, 218, 249.

CORNU: telluric lines, 63, 64.

CORONA, 16, 73–75; spectrum of, 74.

CROSSLEY REFLECTOR, 42, 45.

Cygnus: nebula in, 44.

DARWIN, CHARLES: *Origin of Species*, 1; correlation in research, 97.

DARWIN, SIR GEORGE: tidal friction, 183; meteoroidal swarm, 183, 204.

DESLANDRES: level of calcium flocculi, 90; spectra of flocculi, 96; spectroheliograph, 96; Foucault siderostat, 131.

DRAPER, 41, 54.

ECHELON, 65.

ECLIPSE: solar, 73; apparatus, 75.

ELLERMAN: work with Kenwood spectroheliograph, 86; work with Rumford spectroheliograph, 89; work with 5-foot spectroheliograph, 138; photography of spot spectra, 152, 163.

EVERSHED: spectroheliograph, 96.

EVOLUTION: early views, 1; general problem, 3.

FACULAE, 15, 71, 72, 85, 86, 90, 146.

FLAGSTAFF, 123.

"FLASH" SPECTRUM, 80.

FLOCCULI: calcium, 85; daily motion, 87, 142, 146; minute, 89; levels, 90; eruptive, 92; hydrogen, 94; iron, 96; heliographic positions, 144; proper motions, 146; level of calcium and hydrogen, 147; levels, 150; areas, 150, 217.

FOUCAULT: siderostat, 131.

FOWLER: magnesium hydride in spots, 163; titanium oxide in red stars, 195.

FOX: measures of Kenwood plates, 144.

FRAUNHOFER: dark lines in solar spectrum, 47; objective prism, 189; stellar spectra, 189.

FROST: stellar spectroscopy, 104, 105; heat radiation of sun-spots, 149; Trapezium stars, 189; "*Orion*" type stars, 190.

FURNACE: electric, 160.

GALE: metallic spectra, 159.

GALILEO: early discoveries, 9.

GLOBE MEASURING MACHINE, 144.

GRATINGS: Rowland, 56-59, 235, 236; Michelson, 65, 66, 236; Jewell, 63.

GREENWICH OBSERVATORY: spot positions, 144.

HARVARD OBSERVATORY: refractor, 41; objective prism, 189; stellar spectra, 201.

HELIOMICROMETER, 144.

HELIUM: in Sun, 78, 79; terrestrial, 78; in "Orion" stars, 79; in nebulae, 190.

HERSCHEL, SIR JOHN: clusters and nebulae, 46.

HERSCHEL, SIR WILLIAM: clusters and nebulae, 46; condensation of nebulae, 187.

HIGGS: map of solar spectrum, 62.

HOOKER, J. D.: gift of 100-inch mirror, 238.

HOOKER EXPEDITION, 30, 128.

HOOKER TELESCOPE, 238-42.

HUGGINS: stellar spectra, 53; prominences, 54, 76; spectrum of nebulae, 54; helium, 79; stellar motions, 105; stellar heat, 171; stellar evolution, 199; temperature of nebulae, 207.

HYDROGEN: spectrum, 78; in stars, 79, 170, 191, 193, 195, 199, 200, 206; in prominences, 83; in nebulae, 190; in meteorites, 205.

HYDROGEN FLOCCULI, 93-95; level, compared with calcium, 147.

INTERFEROMETER, 65.

JANSSEN: prominences, 54, 76; solar photography, 70.

JEWELL: telluric lines, 63; gratings, 66.

JULIUS: anomalous dispersion theory, 148.

KAPTEYN: structure of universe, 202.

KEELER: spiral nebulae, 3, 45; photography with Crossley reflector, 42; *Saturn's* rings, 182; chief nebular line, 205.

KENWOOD OBSERVATORY, 83; spectroheliograph, 84; spot spectra, 152.

KIRCHHOFF: explanation of solar spectrum, 51-53.

KIRKWOOD: nebular hypothesis, 185.

KODAIKANAL OBSERVATORY, 119.

LABORATORY: Yerkes Observatory, 107; Solar Observatory, 156.

LANE'S LAW, 191.

LANGLEY: sun-spots, 69; photospheric granules, 69-71; color of Sun, 193; solar radiation, 214; bolometer, 215.

LAPLACE: nebular hypothesis, 2, 175-86.

LICK OBSERVATORY, 42, 119, 120, 205.

LICK TELESCOPE, 26, 41.

LITTROW SPECTROGRAPH; laboratory, 156; of Snow telescope, 134, 153; of "tower" telescope, 232; wooden, 246-48.

LOCKYER: prominences, 54, 76; helium, 78; sun-spot spectra, 151; dissociation in sun spots, 151; temperature of sun-spots, 152; temperature of stars, 173; enhanced lines, 194; stellar classification, 194, 207; meteoritic hypothesis, 204-8.

MAGNESIUM HYDRIDE: in sun-spots, 163.

MAGNIFYING POWER, 22.

Mars: period of inner satellite, 183.

MAUNDER: band lines in spots, 152.

MAXWELL: *Saturn's* rings, 182.

METEORITES: spectra, 205.

MICHELSON: interferometer, 65; standard wave-lengths, 65, echelon, 65; gratings, 65, 66, 236.

MILKY WAY: photographs of, 30-33.

MILLS SPECTROGRAPH, 167.

MIRROR: 60-inch, figuring, 219-26: method of testing, 222, 224-26; 100-inch, 238-41.

MIRRORS: distortion, 137, 138, 231-35, 240.

MOMENTUM: moment of, 185.

MOON: photography of, 33.

MONT BLANC, 119.

MOULTON: criticisms of nebular hypothesis, 182-86.

MOULTON AND CHAMBERLIN: planetesimal hypothesis, 208-10.

MOUNT ETNA: expedition to, 116-19.

MOUNT HAMILTON, 119, 120.

MOUNT WILSON, 123-30.

MOUNT WILSON SOLAR OBSERVATORY: origin, 110; plan of research, 121; site, 123-30; Snow telescope, 132-38; work with spectroheliograph, 139-50; sun-spot spectra, 153-64; laboratory, 155-58, 160; stellar spectroscopy, 167-71; 60-inch reflector, 219-29; "tower" telescope, 232-35; 100-inch reflector, 238-42.

MOUNTAINS: as observatory sites, 113-30.

NEBULA: spiral in *Canes Venatici*, 38, 39; in *Andromeda*, 41, 44, 45; in *Cygnus*, 44; in *Orion*, 44, 188-90; in *Draco*, 54; Laplace's, 177.

NEBULAE: spiral, 7, 38, 39, 41, 44, 45, 188, 203; relationship to stars, 3, 32, 55, 177, 187-90, 198-201, 206, 207, 209, 210; and clusters, 18, 46, 47, 54; in Milky Way, 31, 32; in *Pleiades*, 44, 129, 198, 202; spectrum of, 54, 190, 205; condensation, 178-81, 183, 187, 200, 201, 212; planetary, 187; temperature of, 207.

NEBULAR HYPOTHESIS, 2, 175-86.

NEBULUM, 204.

Neptune: orbits of satellites, 183.

NEWTON: analysis of sunlight, 47; advantages of high altitudes, 111.

NICHOLS: stellar heat, 172.

OLMSTED: calcium hydride in spots, 163.

Origin of Species, 1.

Orion NEBULA, 44, 188–90; *Trapezium* stars, 188, 190.

"*Orion*" TYPE STARS, 79, 190.

PHOTOGRAPHY: advantages, 28; star trails, 29; with camera, 29–33; clusters, 33, 44; Moon, 33, 34; with Yerkes telescope, 33–36; with reflectors, 40–45; of nebulae, 41–45, 203; solar spectrum, 60–64, 247, 248; Sun, 70–72, 244, 245; eclipse, 74–76; with spectroheliograph, 81–96, 139–42, 149, 150, 236, 237, 248; stellar spectra, 104, 105, 165–71, 189–97, 203; corona, without eclipse, 115–18; Milky Way, 128, 129; with Snow telescope, 137, 138; sun-spot spectra, 152–54; metallic spectra, 158–62.

PHOTOSPHERE: structure, 69–72.

PHYSICS: fundamental importance of, 5.

PIC DU MIDI, 119.

PICKERING, E. C.: objective prism, 189; stellar spectra, 201.

PIKE'S PEAK: expedition to, 115, 116.

PLANETESIMAL HYPOTHESIS, 208–10.

Pleiades, 18, 44, 129, 177, 198, 202.

POTSDAM ASTROPHYSICAL OBSERVATORY, 100, 167.

PRISM: formation of spectrum, 48; objective, Fraunhofer, 189; objective, Pickering, 189; glass, 236.

PROMINENCES, 15; nature of, 76; without eclipse, 77; spectrum, 78; seen with open slit, 81; quiescent and eruptive, 81, 93; photography of, 82; H and K in, 84.

PYRHELIOMETER, 215.

QUARTZ: fused, for telescope mirrors, 233–35.

RADIOMETER, 172.

RADIUM, 212, 213.

RAMSAY: discovery of helium, 78.

REVERSING LAYER, 143.

RITCHEY: photographs of Moon, 33, 34; photography with Yerkes telescope, 33, 36; 24-inch reflector, 43; photography with reflector, 44; telescope construction, 43, 219–30; 100-inch reflector, 238–40.

RITCHEY AND BARNARD: photography of corona, 76.

ROBERTS: *Andromeda* nebula, 41.

ROSSE: 6-foot reflector, 38, 39.

ROTATION: solar, by spots, 143; by faculae, 143; by flocculi, 143, 146.

ROWLAND: gratings, 56–59; composition of Sun, 62; map of solar spectrum, 62; solar spectrum wave-lengths, 62.

RUMFORD SPECTROHELIOGRAPH, 88.

RUNGE: helium, 79.

RUTHERFURD: stellar spectra, 2, 53; gratings, 57.

SATURN: ring system, 179; constitution of rings, 182; revolution of rings, 184.

SCHUSTER: stellar evolution, 199.

SECCHI: stellar spectra, 53; prominences, 76; classification of stellar spectra, 170.

Sirius: spectrum, 191.

SMITH, PIAZZI: Teneriffe expedition, 119.

SMITHSONIAN OBSERVATORY, 214.

SNOW TELESCOPE, 132–38.

SOLAR UNION, 218, 248.

SPECTRA: stellar, 2, 18, 104, 105, 164–71, 189–91, 193–203, 207, 208; nebulae, 18, 54, 203–7; solar, 47, 51–53, 60–64, 215; continuous, 49, 51; bright-line, 49–53, 60, 61, 107, 141, 157–63, 205; dark-line, 51–54, 93, 94; prominences, 54, 76–81; grating, 58–60; chromosphere, 78–81; "flash," 80; flocculi, 85, 86, 90, 91, 93–96; faculae, 90; sun-spots, 108, 151–64; arc, 159–62; electric furnace, 160, 161; *Saturn's* ring, 182; Sun, center and limb, 192; "enhanced" lines, 194.

SPECTROGRAPH: Bruce, 104, 167; Littrow, 134, 153; laboratory, 156; Mills, 167; Potsdam, 167; grating, for stars, 167, 228; of "tower" telescope, 232; wooden, 246–48.

SPECTROHELIOGRAPH: principle of, 82; Kenwood, 84; Rumford, 88; use of dark lines, 93; 5-foot, 139; operation, 141; 30-foot, 233; future development, 236.

SPECTROSCOPE: Kirchhoff's, 51; plane grating, 58, 77; concave grating, 59, 60; objective prism, 80, 189.

SPECTROSCOPIC BINARIES, 105.

SPENCER: nebulae, 47.

SPURIOUS DISK, 23.

STARS: clusters, 18, 46; colors, 18, 170, 173, 191, 193, 195, 199; size of image, 23; clouds, 31; spectra, 53, 104, 105, 164–71, 173, 174, 189–203, 207, 208, 241; twinkling, 111; heat radiation, 171; red, 173, 195–97, 208; temperature, 173; helium, 190; "*Orion*" type, 190; white, 191; dark, 197.

STEREOCOMPARATOR, 147.

SUN: visual appearance, 15, 68; composition, 16; activity, 16, 217; as a star, 17; line absorption, 53; absorption in atmosphere, 68; direct photography, 70, 245; inclination of axis, 143; rotation, 143, 146; contraction, 191; spectra of center and limb, 192; radiation, 212–16.

SUN-SPOTS, 15, 69; periodicity, 16; level, 71, 148; heliographic positions, 143–6; dissociation in, 151; darkness, 151, 163; spectrum, 151–64; temperature, 163.

TELESCOPE: magnifying power, 22; brightness of image, 22; resolving power, 23; large and small, 24–27; fixed, 131, 232; "tower," 232.

TELESCOPE: reflecting, Rosse, 38; development of, 38-45; advantages, 42; Crossley, 42, 45; 24-inch, 43; Snow, 132-38; 60-inch, 219-30; 100-inch, 238-42.

TELESCOPE: refracting, 21, 230; Yerkes, 25, 26, 33-36, 43, 88, 101-4; Lick, 26, 41; Burnham's 27; camera, 28-3; Bruce, 29, 30; Kenwood, 33, 84; development of, 41.

TELLURIC LINES, 63, 64.

TENERIFFE EXPEDITION, 119.

TITANIUM OXIDE: in sun-spots, 162.

"TOWER" TELESCOPE, 232.

Trapezium STARS, 188, 190.

TURNER: coelostat, 132.

TWINKLING OF STARS, 111.

Uranus: orbits of satellites, 183.

Vega: heat radiation, 172, 173.

VOGEL: stellar motions, 105.

WADSWORTH: reflector mounting, 43.

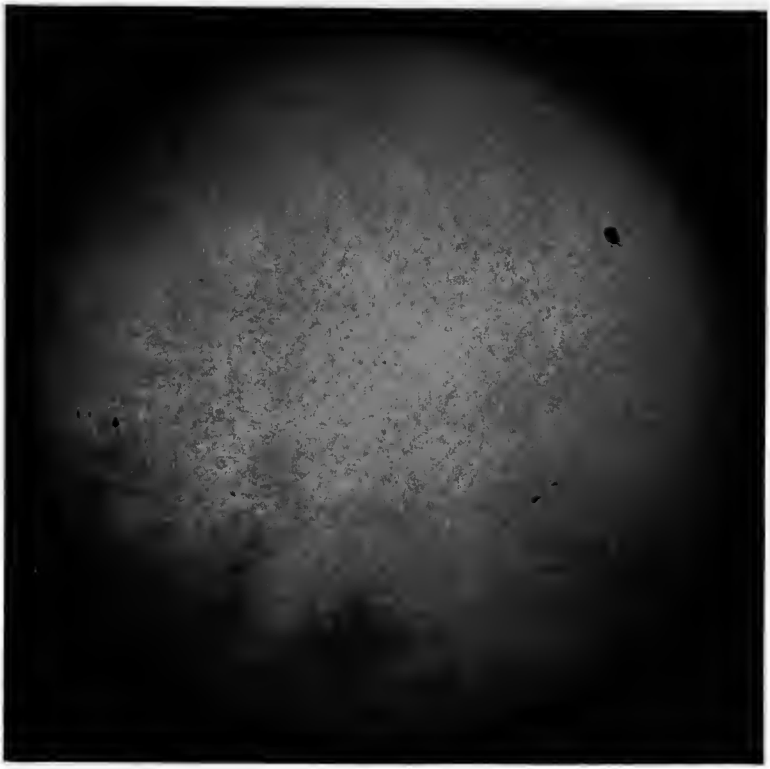
WILSON: sun-spots as cavities, 71.

YERKES OBSERVATORY: policy, 98; origin, 99; plan of building, 100; instrument and optical shops, 106; spectroscopic laboratory, 107; site, 113; coelostat room, 172.

YERKES REFRACTOR: photography, 33-36, 88; mounting, 34, 101; compared with reflector, 44; objective, 101; operation of, 102.

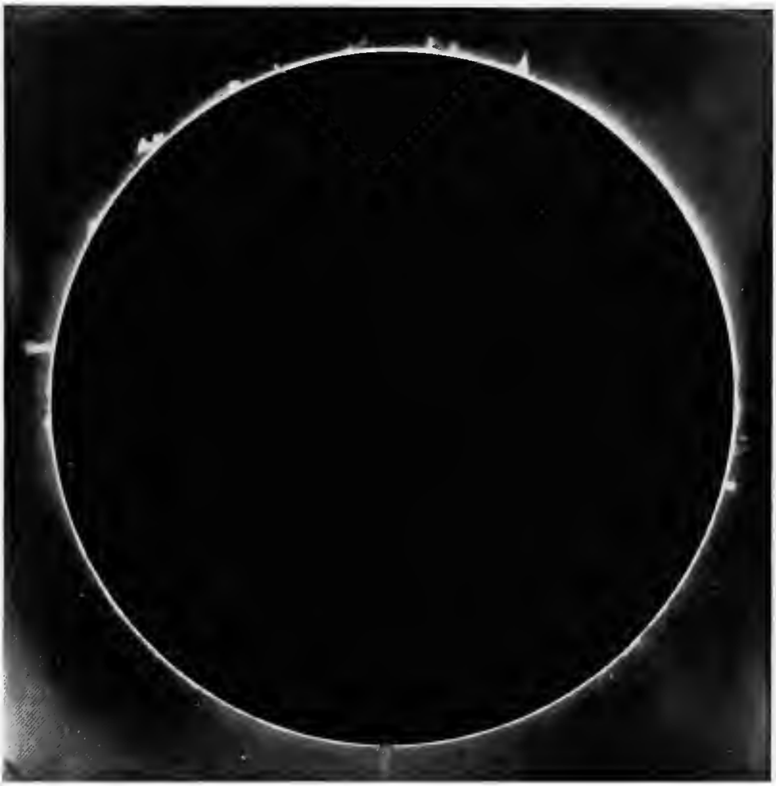
YOUNG: discovery of "flash" spectrum, 80; prominences, 81; H and K in prominences, 84; calcium flocculi, 85; photography of spot spectra, 152.

PLATE II



Direct Photograph, Sh[illegible]g the Sun as it Appears to the Eye

PLATE III



The Solar Chromosphere and Prominences

PLATE IV

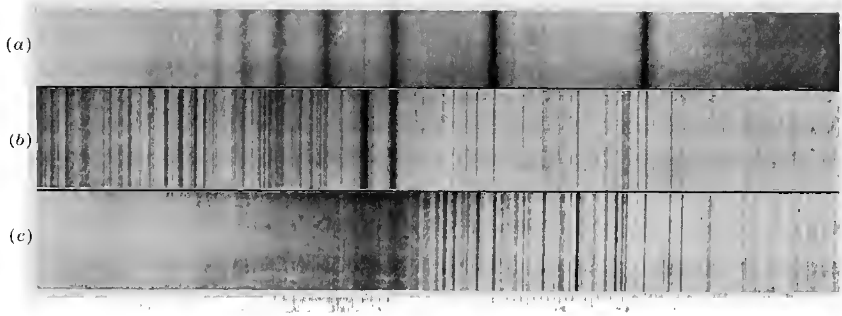


FIG. 1

CHARACTERISTIC SPECTRA OF (a) WHITE, (b) YELLOW, AND (c) RED STARS
(Huggins)

FIG. 2

THE SOLAR CORONA

Photographed by Yerkes Observatory Eclipse Expedition, May 28, 1900 (Barnard and Ritchey)

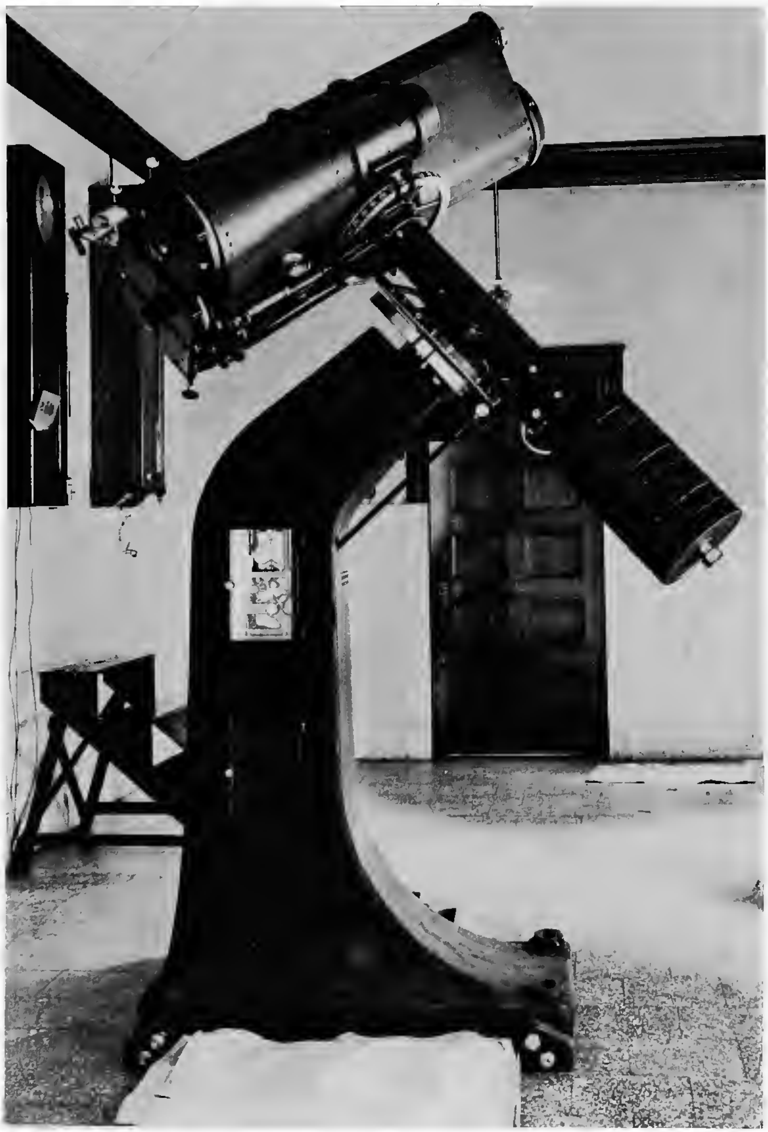
PLATE V

Six-inch Refractor with Which Burnham Discovered 451 Double Stars

PLATE VI

Star Trails Photographed with 2½-inch Portrait Lens
(Ritchey)

PLATE VII



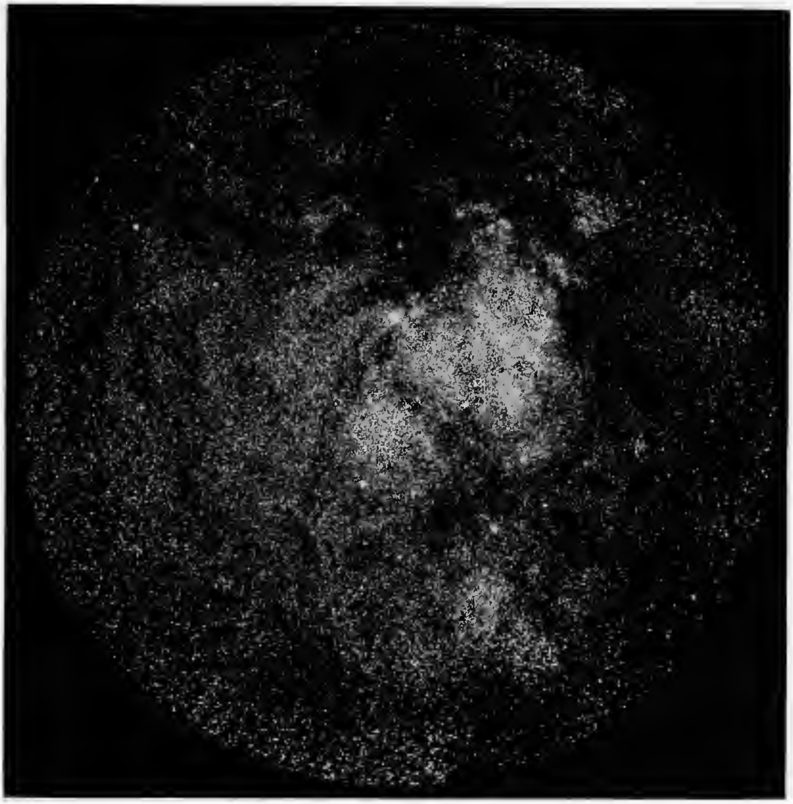
THE BRUCE TELESCOPE OF THE YERKES OBSERVATORY

PLATE VIII

STAR CLUSTER *Messier* 11 AND THE SURROUNDING MILKY WAY

Small-scale photograph taken with lantern lens (Barnard)

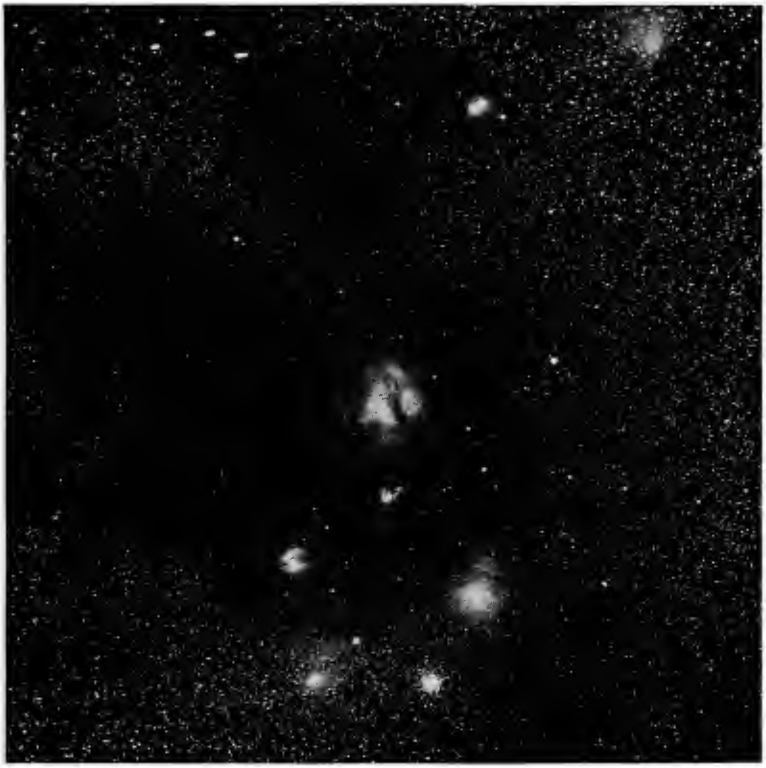
PLATE IX



STAR CLUSTER *Messier* 11 AND THE SURROUNDING MILKY WAY

Larger-scale photograph taken with 10-inch Bruce telescope (Barnard)

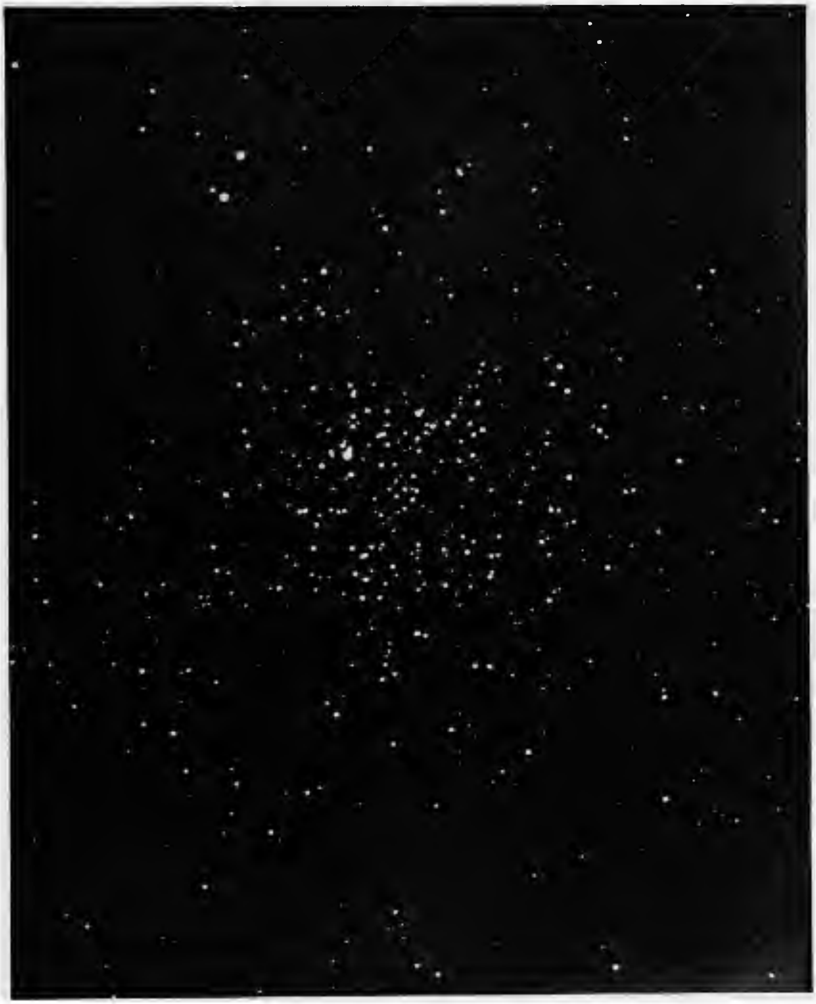
PLATE X



THE MILKY WAY NEAR ρ *Ophiuchi*

Photographed with 10-inch Bruce telescope (Barnard)

PLATE XI



STAR CLUSTER *Messier* 11

Large-scale photograph taken with 40-inch Yerkes telescope (Ritchey)

PLATE XII

The Moon

Photographed with the 12-inch Kenwood refractor (Ritchey)

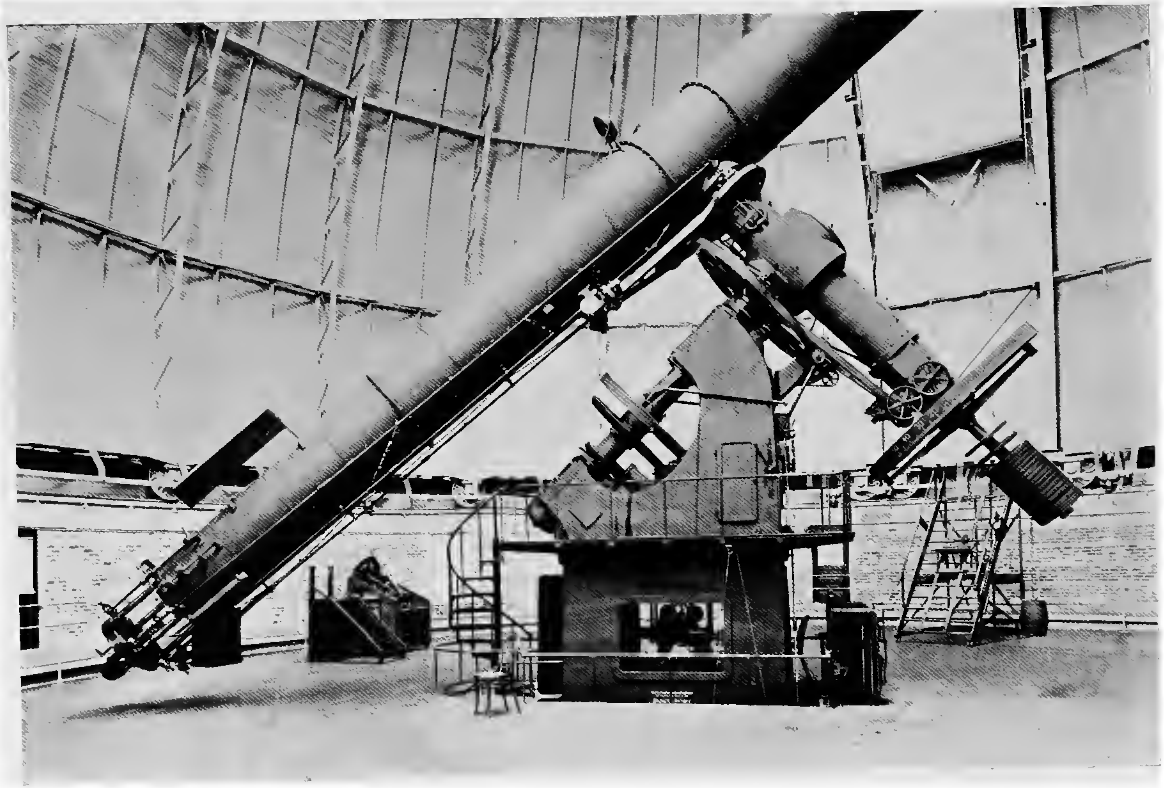
PLATE XIII

LUNAR CRATER *Theophilus* AND SURROUNDING REGION
Photographed with the 40-inch Yerkes refractor (Ritchey)

PLATE XIV

The 40-inch Refractor of the Yerkes Observatory

PLATE XV

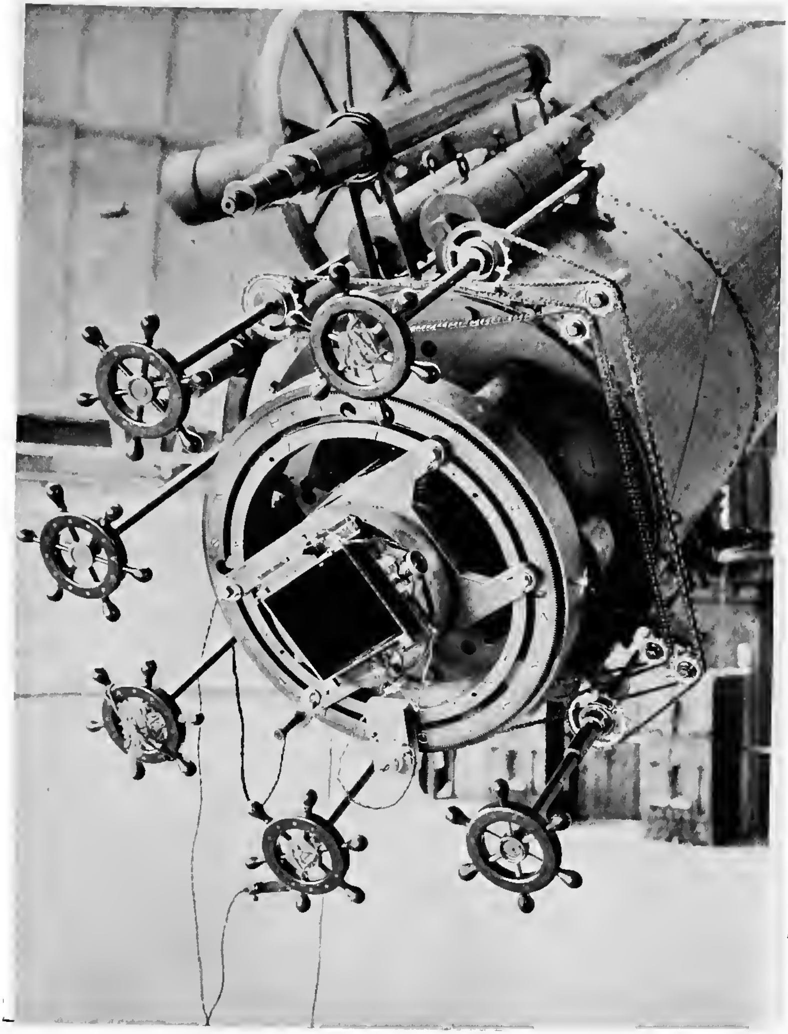


THE 40-INCH YERKES REFRACTOR
Showing rising-floor at highest position

PLATE XVI

90-foot Dome of the Yerkes Observatory

PLATE XVII



Eye-End of Yerkes Telescope

Showing double-slide plate-holder

PLATE XVIII

THE 24-INCH REFLECTOR OF THE YERKES OBSERVATORY

PLATE XIX

STAR CLUSTER *Messier* 13

Photographed with tbe 24-inch reflector of the Yerkes Observatory (Ritchey)

PLATE XX

STAR CLUSTER *Messier* 13

Photographed with the 40-inch Yerkes refractor (Ritchey)

PLATE XXI

THE GREAT NEBULA IN *Orion*

Photographed with the 24-inch reflector (Ritchey)

PLATE XXII

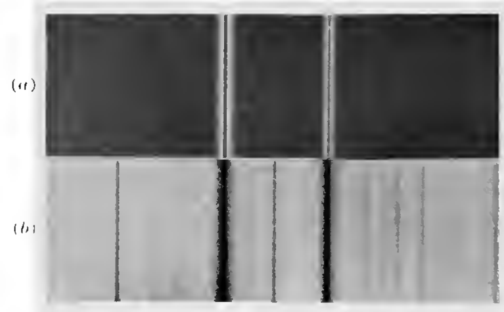


Fig. 1

Comparison of the D Lines of Sodium in Spectra of (a) Electric Arc and (b) the Sun

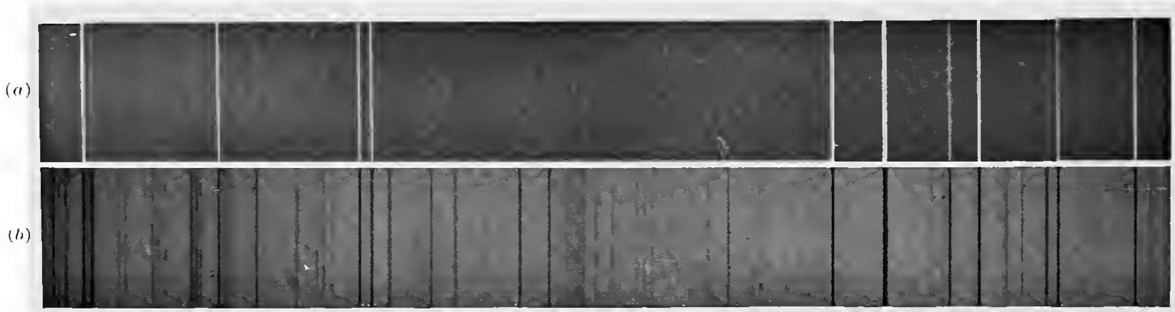


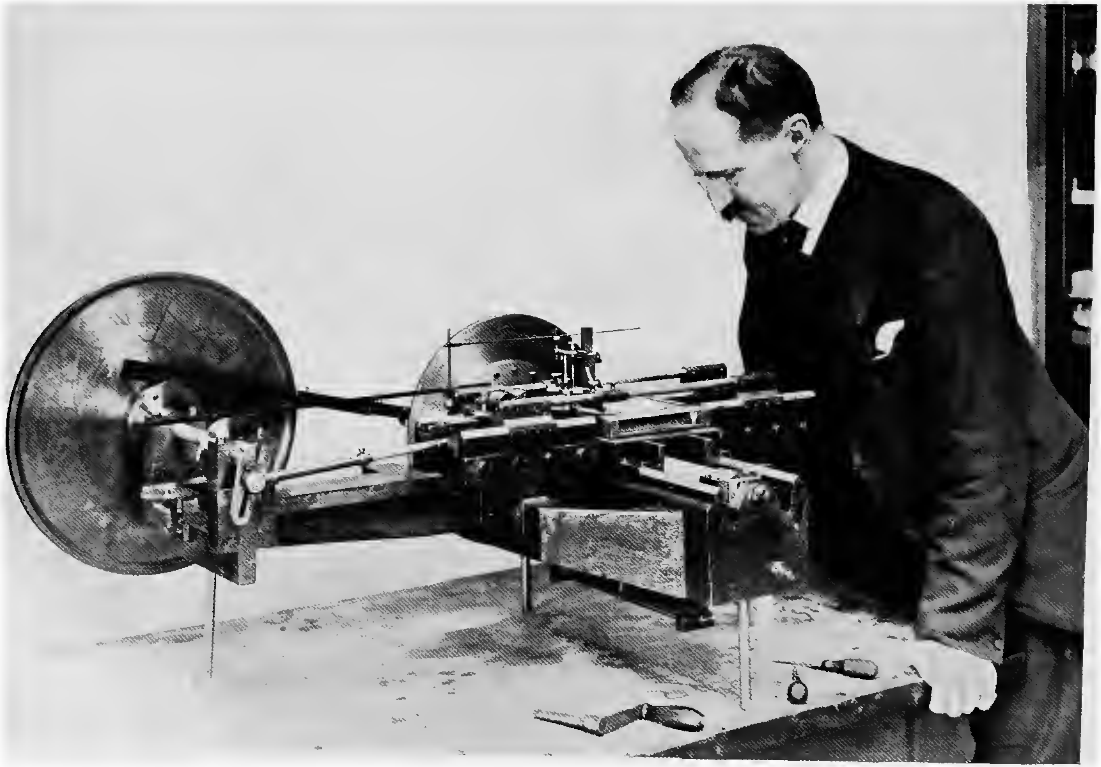
Fig. 2

Comparison of Iron Spectrum in (a) Electric Arc and (b) the Sun

PLATE XXIII

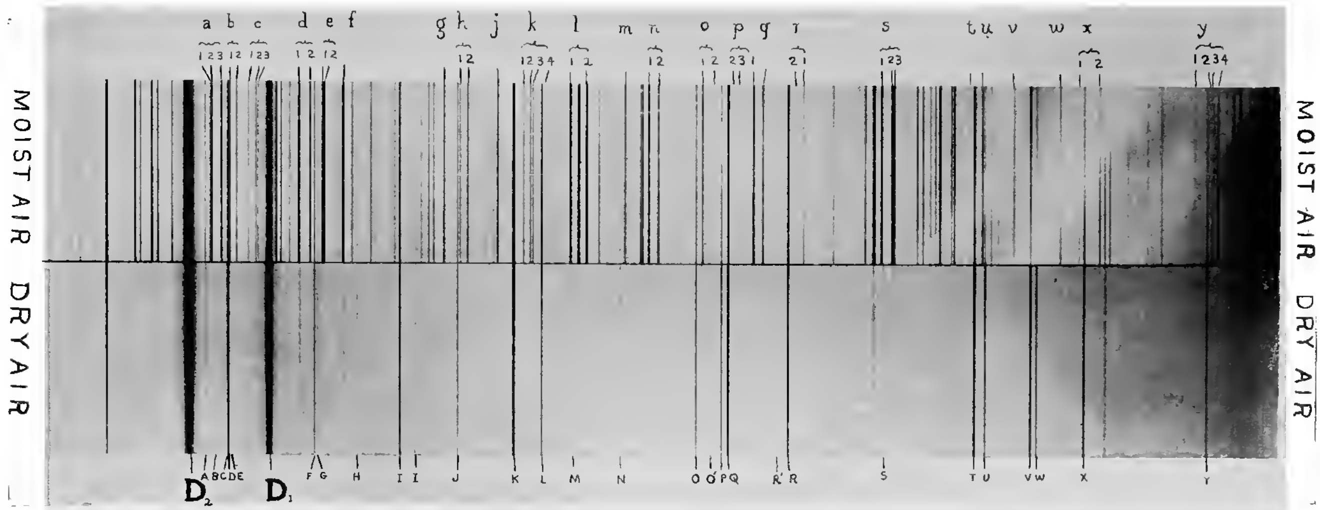
Sir William Huggins

PLATE XXIV



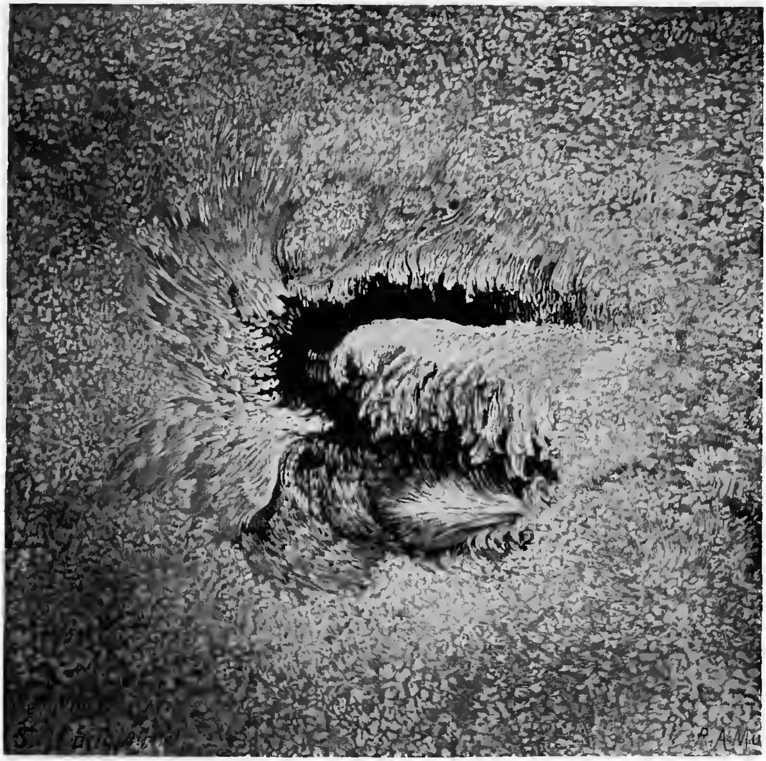
Professor Henry A. Rowland with His Ruling Engine

PLATE XXV



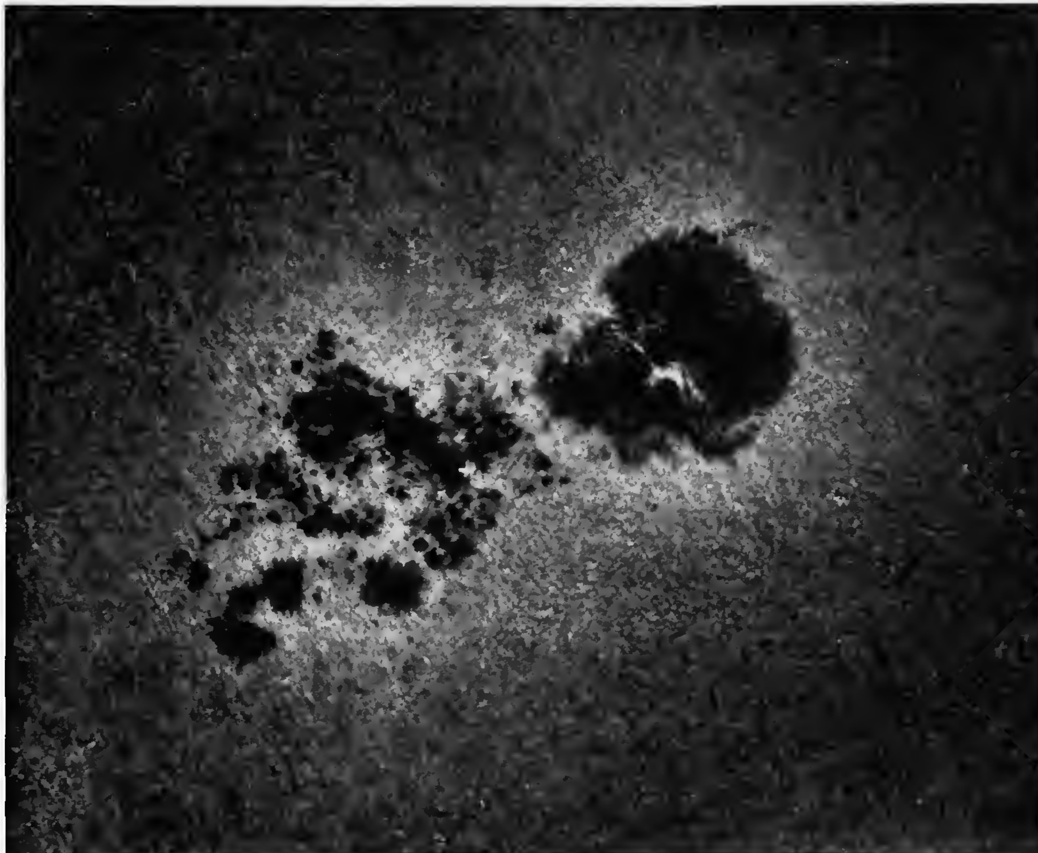
WATER-VAPOR LINES IN THE SOLAR SPECTRUM
(Jewell)

PLATE XXVI



Langley's Drawing of the Typical Sun-Spot of December, 1873

PLATE XXVII



Direct Photograph of the Great Sun-Spot of June 22, 1885 (Janssen)

Scale: Sun's Diameter = 0.888 Meter

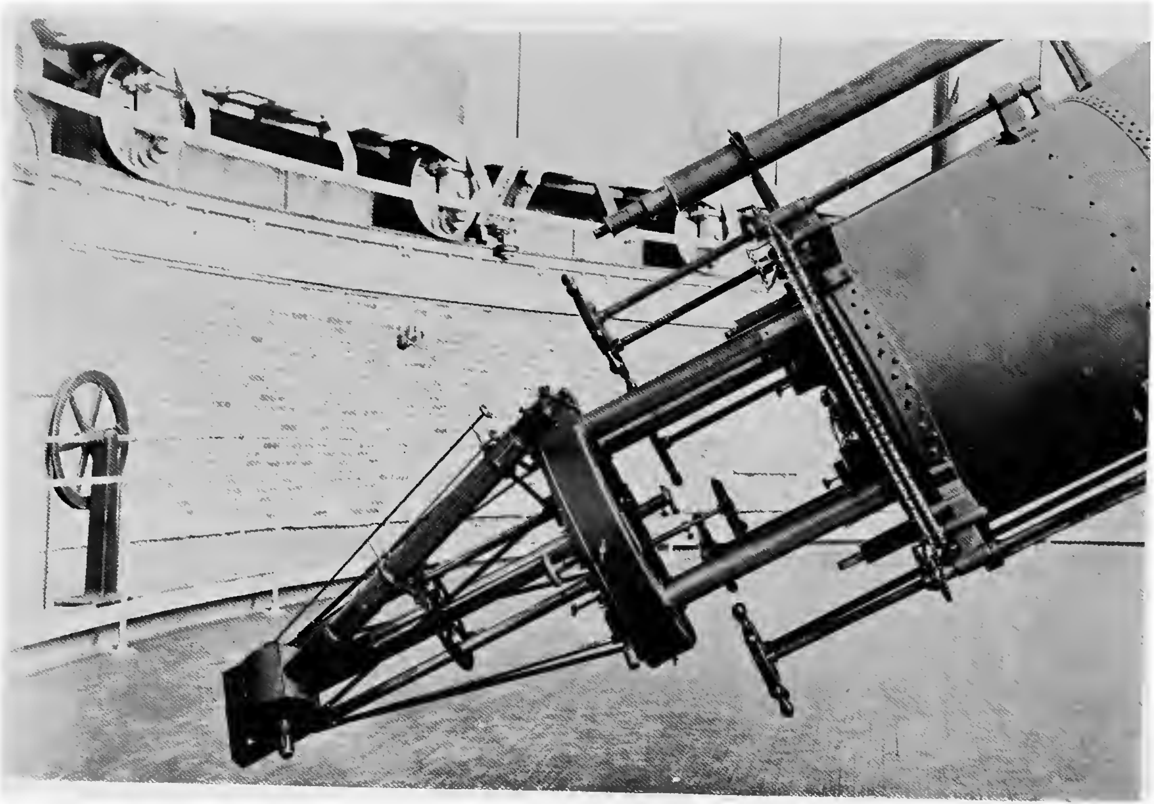
PLATE XXVIII

Coelostat Telescope Used by Yerkes Observatory Expedition at the Solar Eclipse of May 28, 1900

PLATE XXIX

SOLAR PROMINENCES PHOTOGRAPHED AT ECLIPSE OF MAY 28, 1900
(Barnard and Ritchey)

PLATE XXX



Solar Spectroscope Attached to 40-inch Yerkes Refractor

PLATE XXXI

SPECTRUM OF THE SECOND FLASH

Photographed with objective-prism train spectroscope, eclipse of May 28, 1900 (Lord)

PLATE XXXII

H K

(*a*)

(*b*)

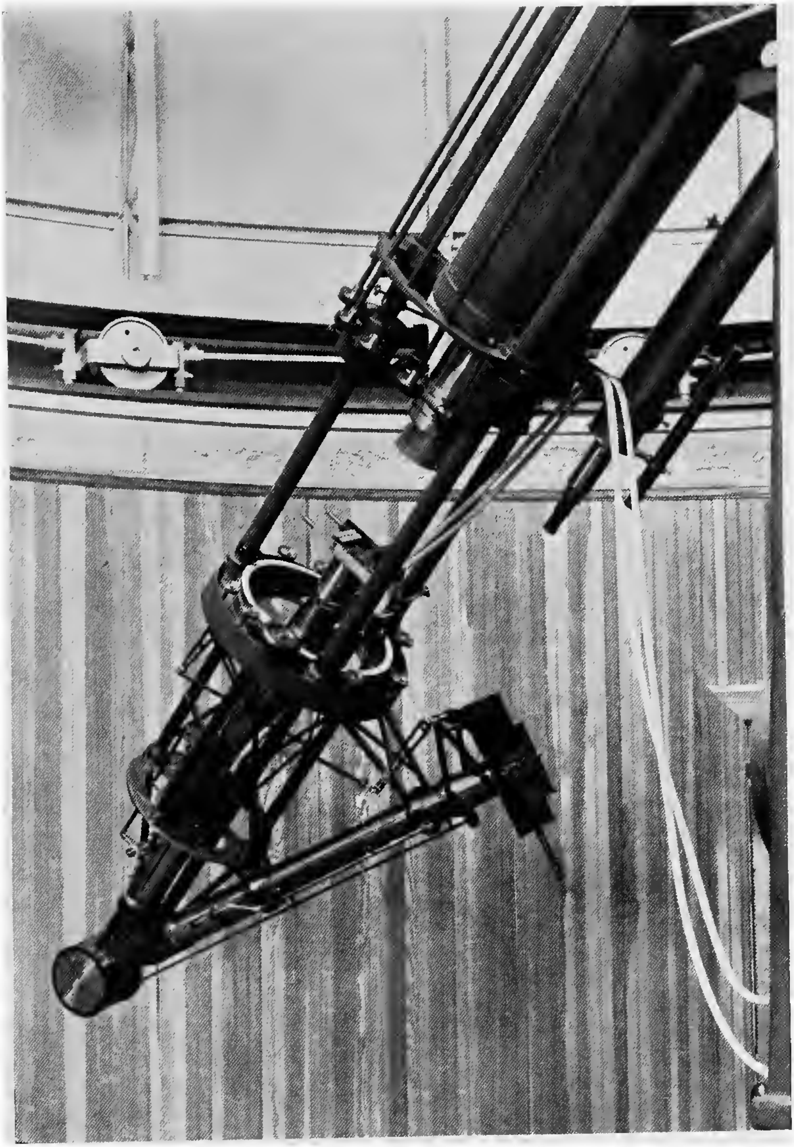
(*c*)

BRIGHT H AND K LINES ON THE DISK (*a*, *b*, and *c*), IN THE CHROMOSPHERE (*b*), AND IN A PROMINENCE (*a*)

PLATE XXXIII

The Kenwood Observatory, Chicago, 1888–1895

PLATE XXXIV



SPECTROHELIOGRAPH ATTACHED TO 12-INCH KENWOOD REFRACTOR

PLATE XXXV

Eruptive Prominence Photographed with the Kenwood Spectroheliograph

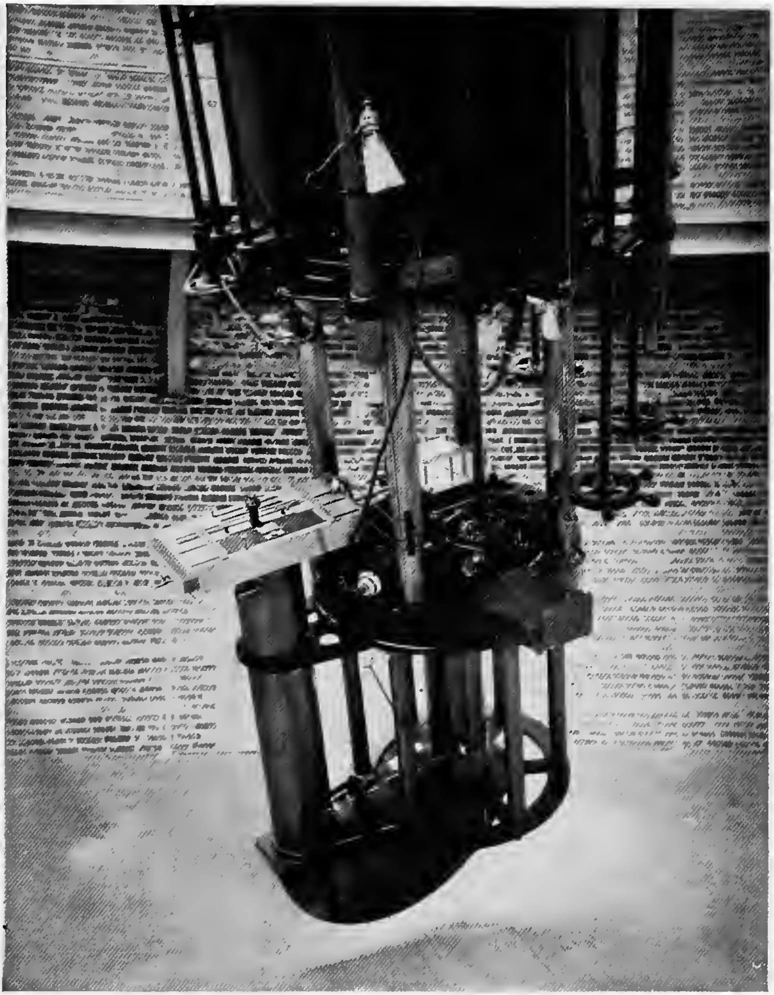
March 25. 1895, $10^h\,40^m$. Height of prominence, 162,000 miles

PLATE XXXVI

ERUPTIVE PROMINENCE SHOWN IN PLATE XXXV PHOTOGRAPHED 18 MINUTES LATER

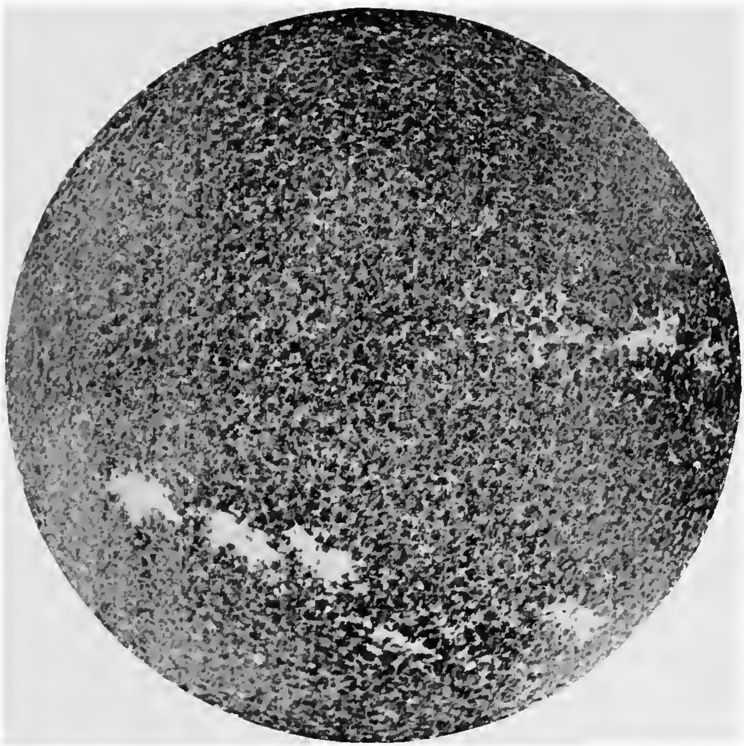
Height of prominence, 281,000 miles

PLATE XXXVII



Rumford Spectroheliograph Attached to 40-inch Yerkes Refractor

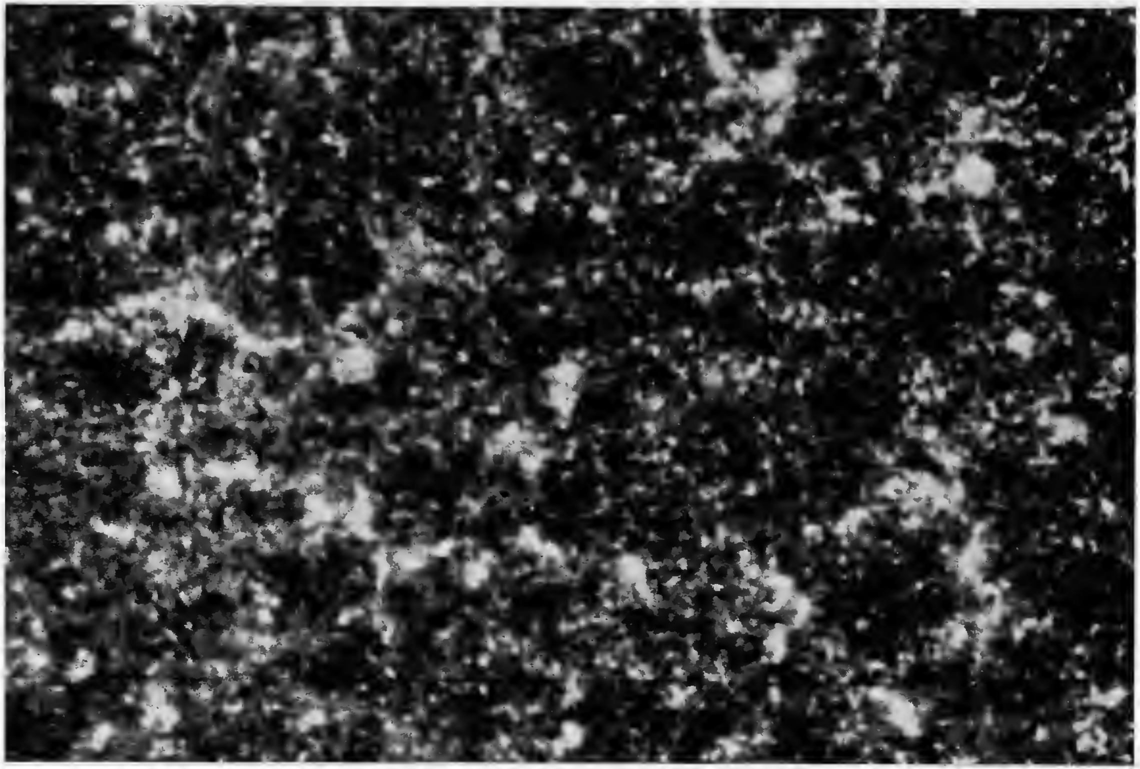
PLATE XXXVIII



The Sun, Showing the Calcium Flocculi

August 12, 1903, $8^h\ 52^m$

PLATE XXXIX



Minute Structure of the H_2 Calcium Flocculi
September 22, 1903. (Scale: Sun's Diameter = 0.890 Meter)

PLATE XL

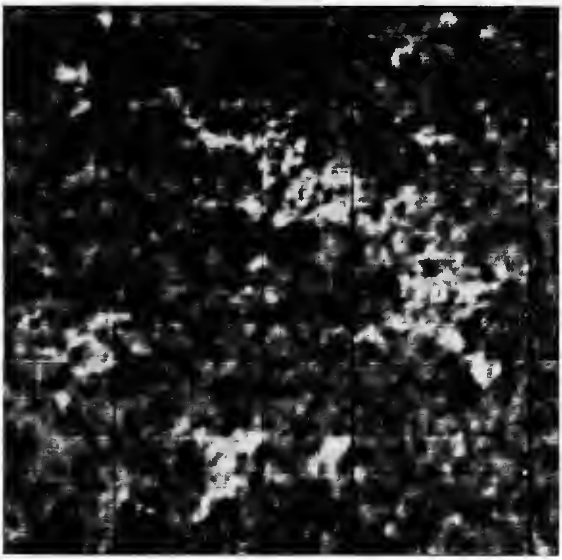


FIG. 1.—3h 40m. Second slit set on H_1

FIG. 2.—3h 31m. Second slit set on H_2 Same region of the Sun as that shown in Fig. 1

MINUTE STRUCTURE OF THE CALCIUM FLOCCULI

September 22, 1903. (Scale: Sun's Diameter = 0.890 Meter)

PLATE XLI

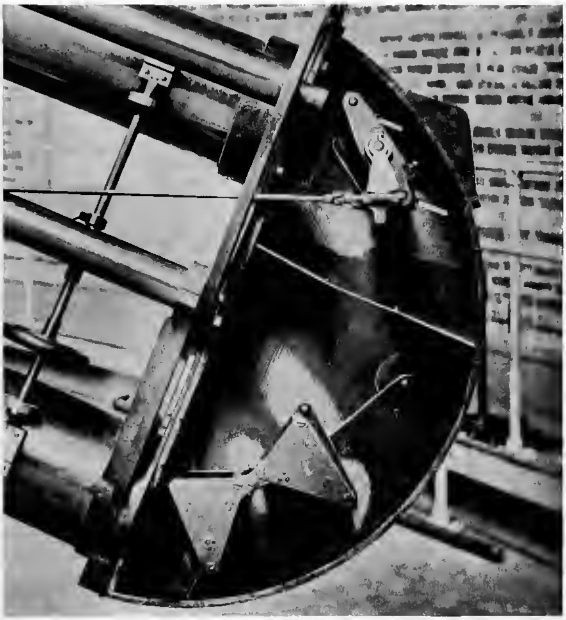


FIG. 1
PRISM TRAIN OF THE RUMFORD SPECTROHELIOGRAPH

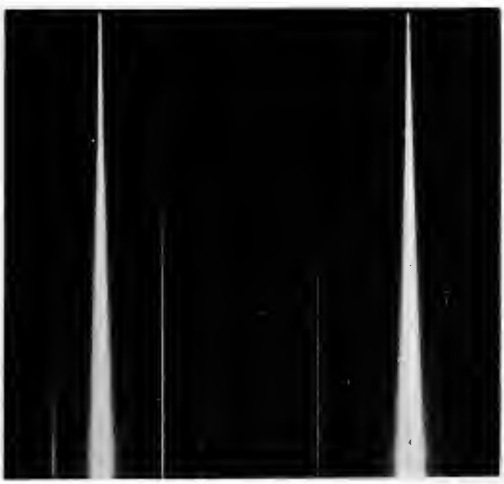
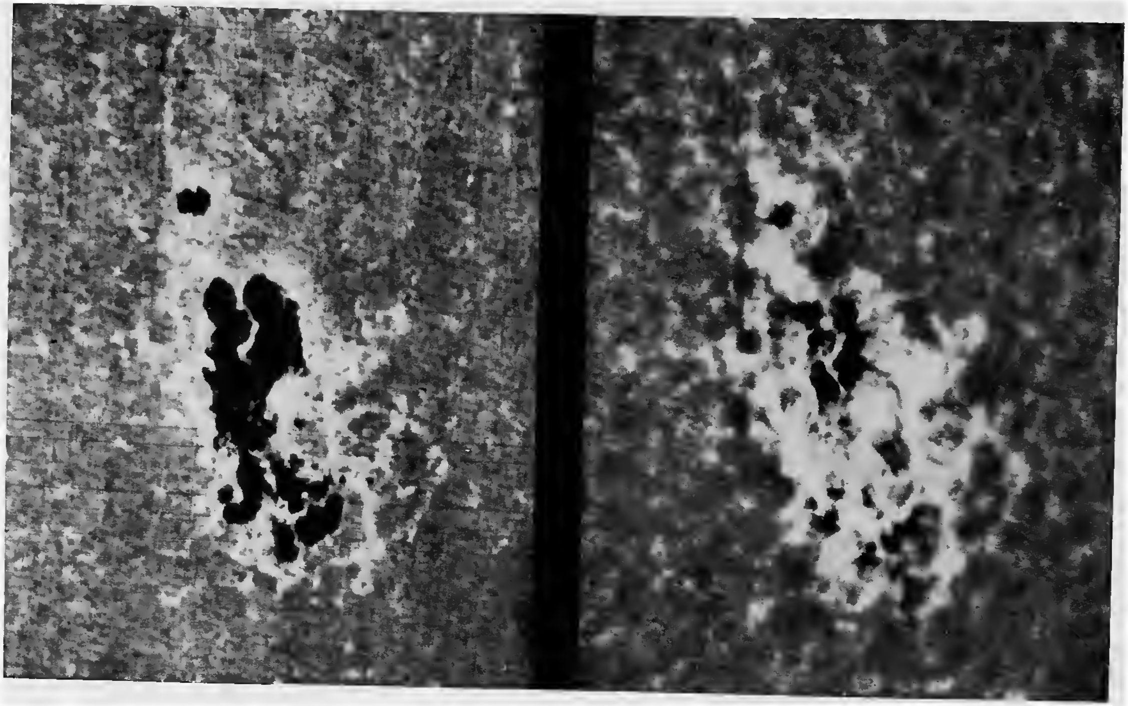


FIG. 2
H AND K LINES OF CALCIUM IN THE ELECTRIC ARC

PLATE XLII



Great Sun-Spot of October, 1903

October 9, 3^h 43^m. Calcium flocculi as shown with second slit set on H_1

October 9, 3^h 30^m. Calcium flocculi as shown with second slit set on H_2 at

PLATE XLIII

N

FIG. 1.—3h 57m. Calcium flocculi (K_2).

E W

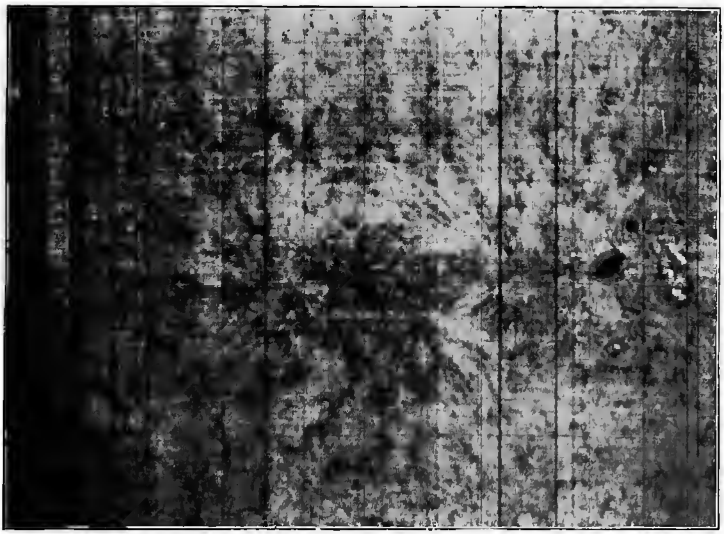
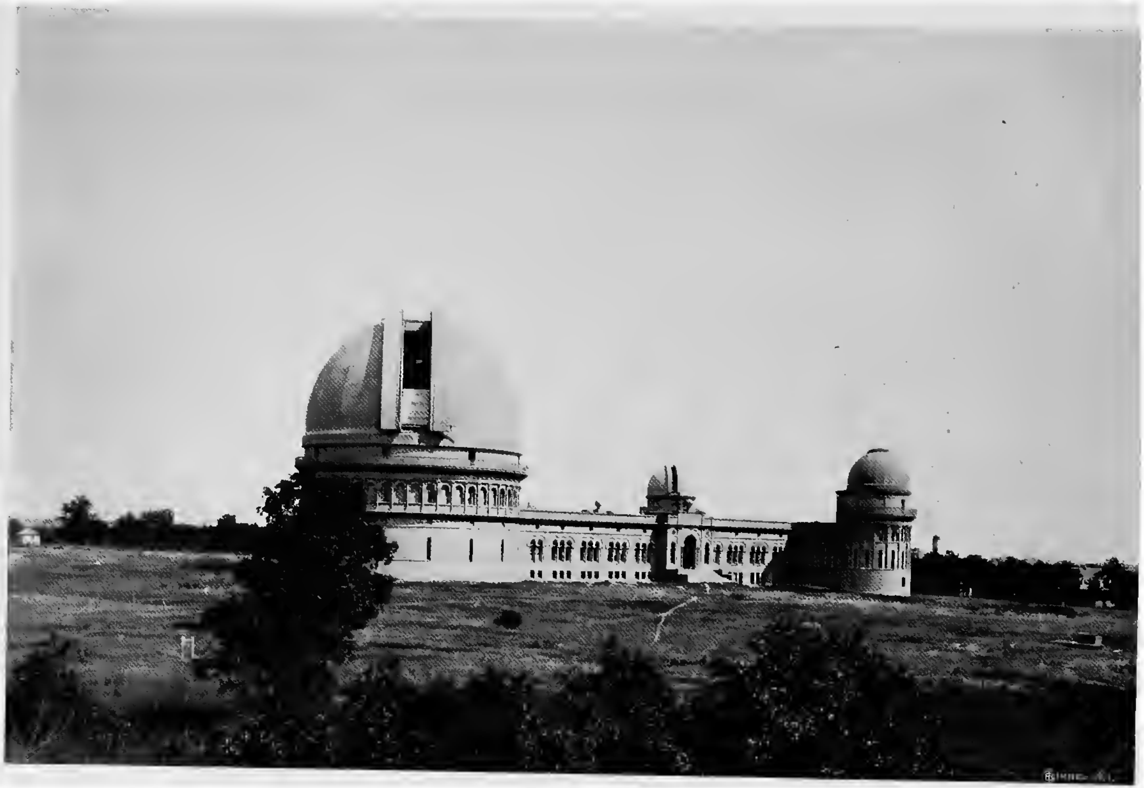


FIG. 2.—11h 0m. Hydrogen flocculi ($H\gamma$) (bright eruptive flocculi west of spot)

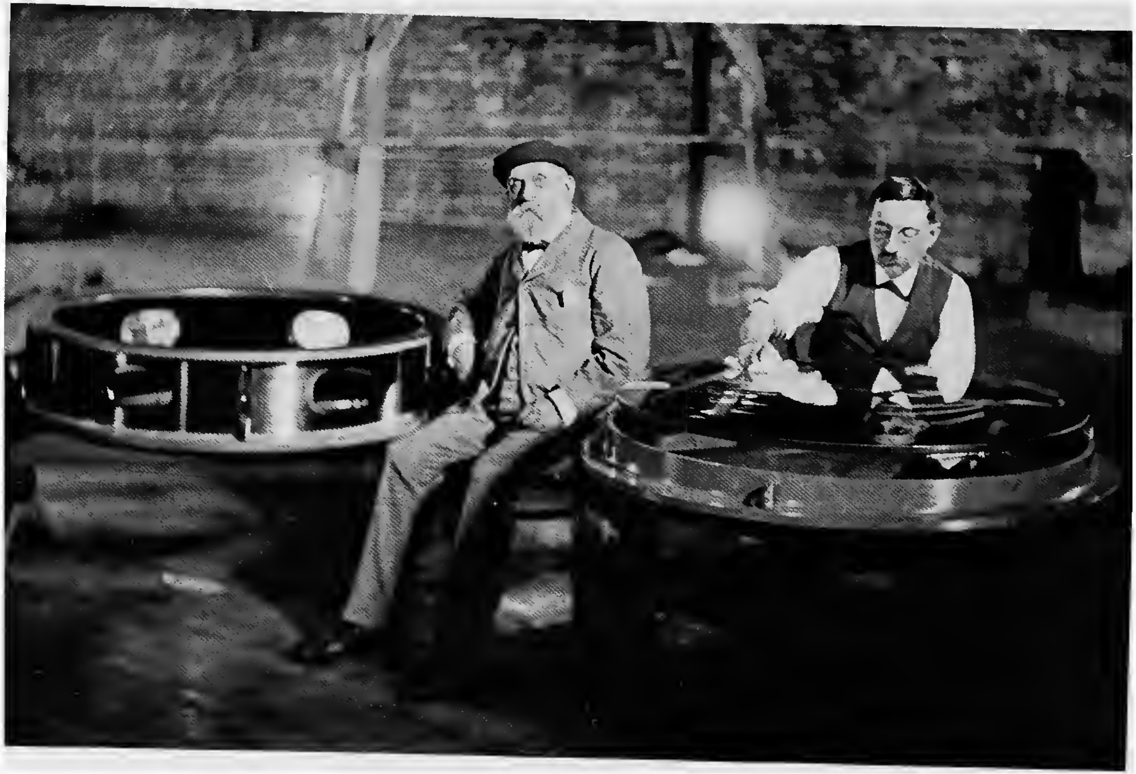
HYDROGEN AND CALCIUM FLOCCULI, JULY 7, 1903

PLATE XLIV



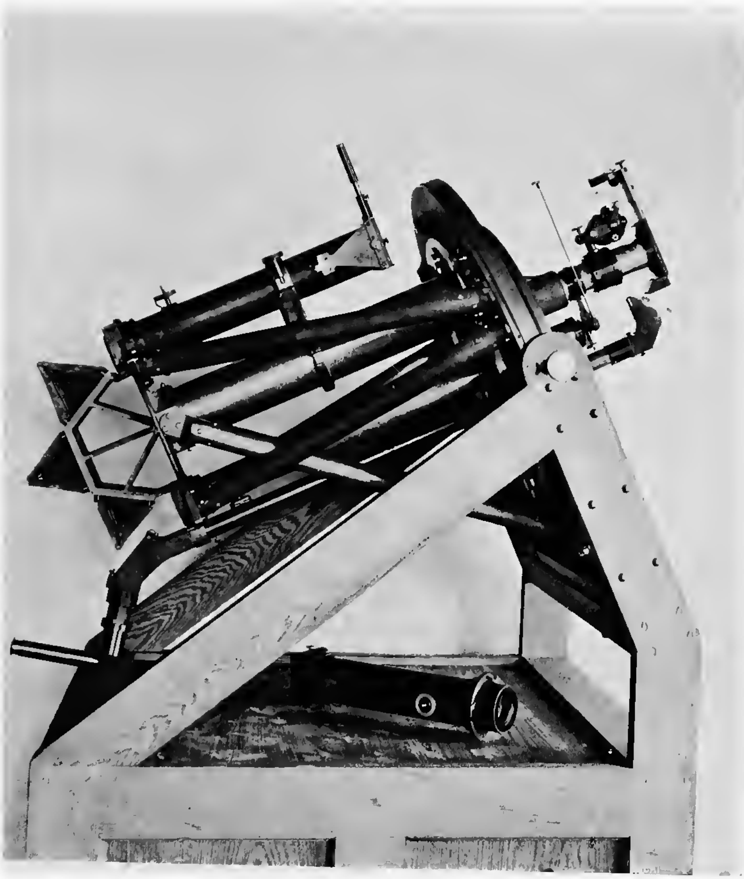
THE YERKES OBSERVATORY FROM THE SOUTHWEST

PLATE XLV



Alvan G. Clark and Carl Lundin with the Crown Lens of the 40-inch Yerkes Objective

PLATE XLVI



THE BRUCE SPECTROGRAPH OF THE YERKES OBSERVATORY

Mounted on its carriage, with constant temperature case removed

PLATE XLVII

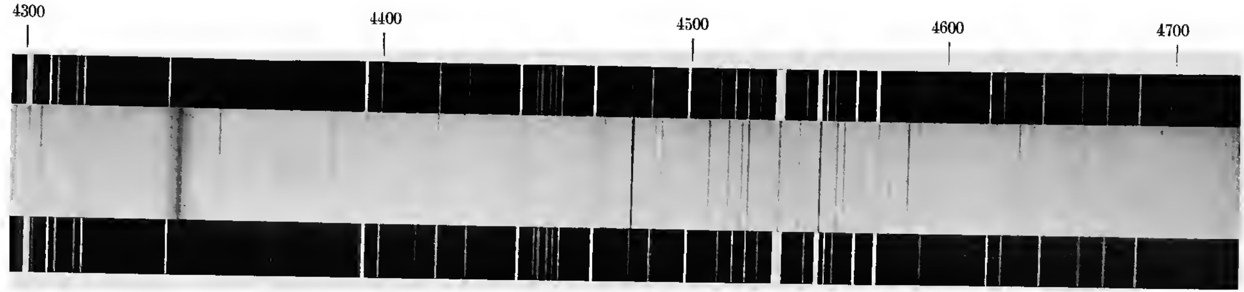


FIG. 1.—*η Leonis*

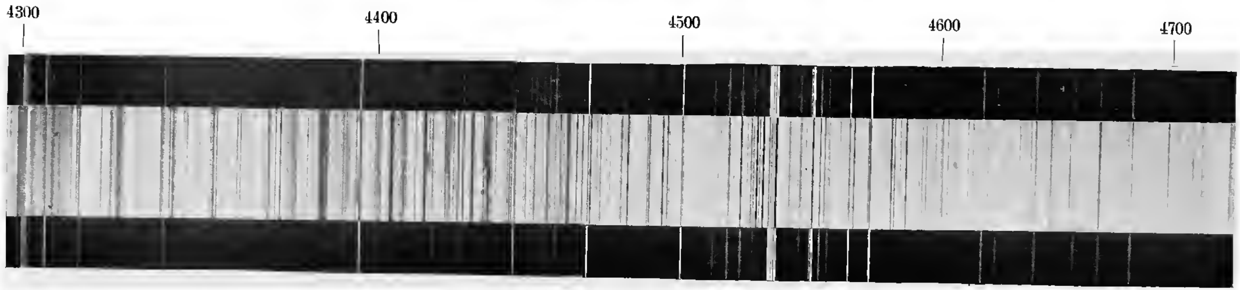


FIG. 2.—*α Boötis* (*Arcturus*)

STELLAR SPECTRA PHOTOGRAPHED WITH THE BRUCE SPECTROGRAPH

(Frost and Adams)

PLATE XLVIII

The Lick Observatory, Mount Hamilton, California

PLATE XLIX

Mount Wilson, as Seen from Mount Harvard

PLATE L

Mount San Antonio
Photographed with telephoto lens from Mount Wilson

PLATE LI

Low-Lying Fog Clouds, as Seen from Mount Wilson

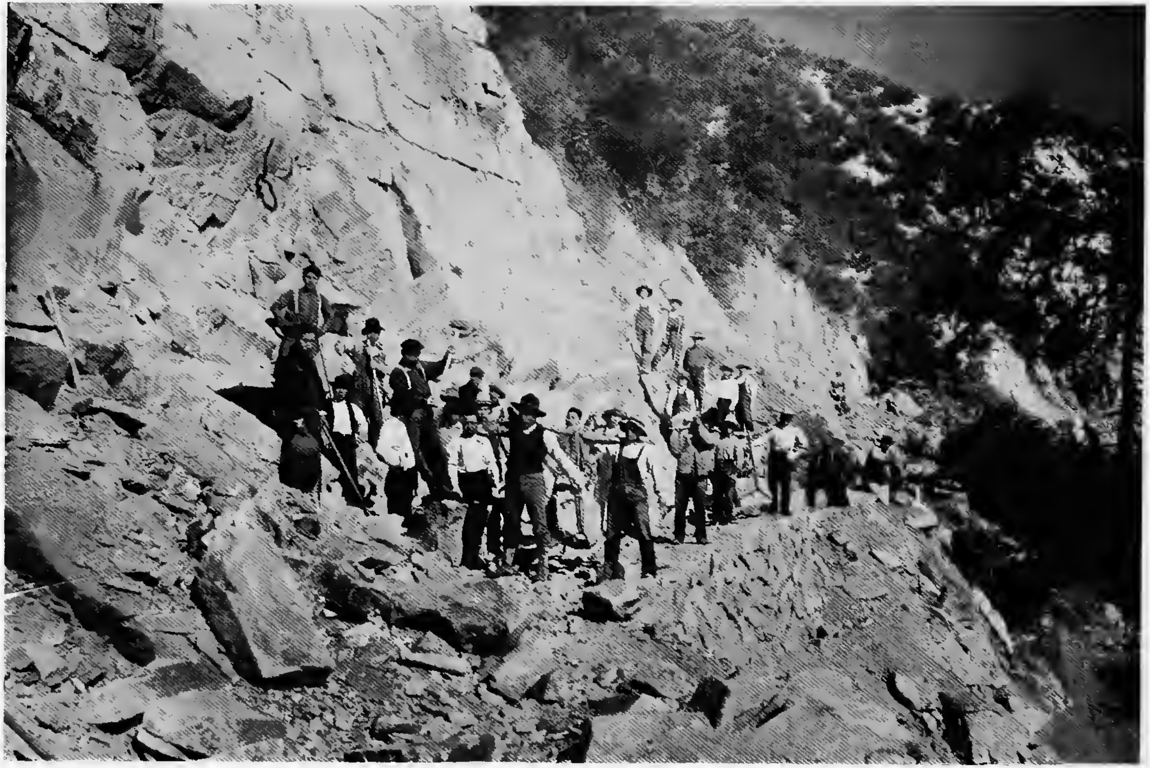
PLATE LII

Lower Part of "New Trail," Showing Pack Train

PLATE LIII

Truck Formerly Used for Hauling Heavy Instruments over "New Trail"

PLATE LIV



WIDENING THE "NEW TRAIL"

PLATE LV

SNOW ON MOUNT WILSON

The "Monastery" after the great storm of January, 1907

PLATE LVI

FIG. 1.—At the Yerkes Observatory. Exposure 40^m

FIG. 2.—At Mount Wilson. Exposure 41^m

STAR CLUSTER *Messier* 35

Photographed with the Bruce telescope (Barnard)

PLATE LVII

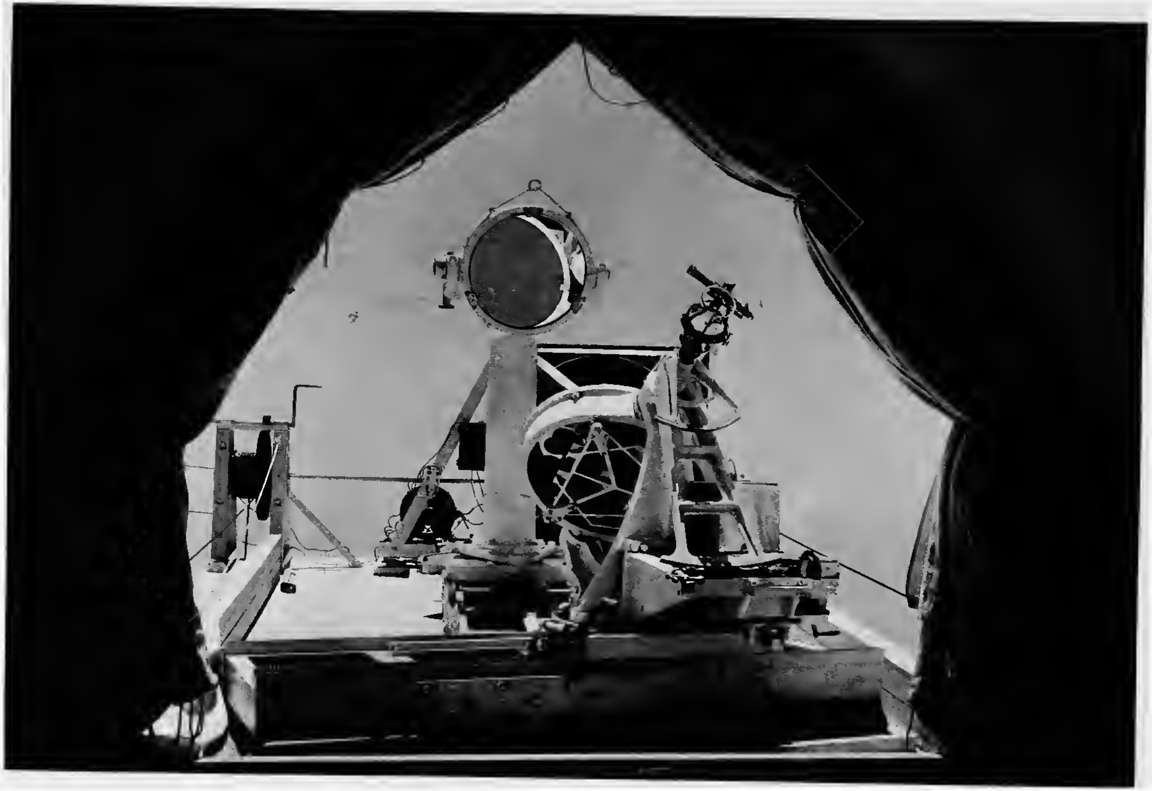
Fig. 1.—At the Yerkes Observatory. Exposure $9^h\ 47^m$

Fig. 2.—At Mount Wilson. Exposure $3^h\ 48^m$

The Pleiades

Photographed with the Bruce telescope (Barnard)

PLATE LVIII



Coelostat and Second Mirror of Snow Telescope

PLATE LIX

Concave Mirror of Snow Telescope

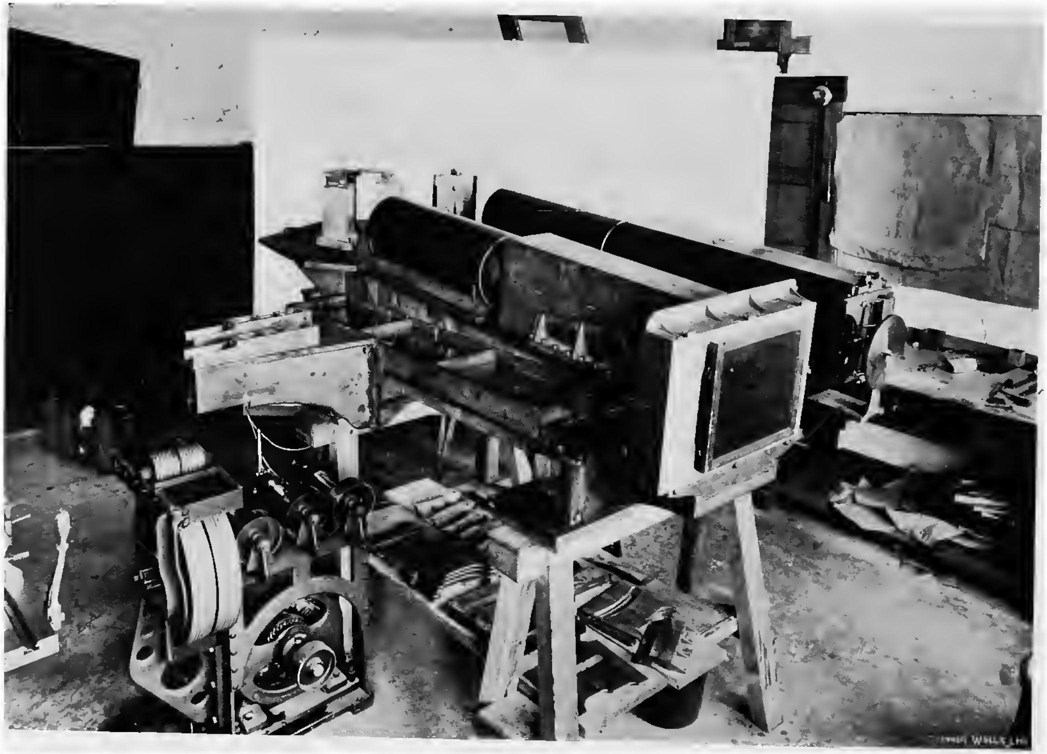
PLATE LX

SOUTH END OF SNOW TELESCOPE HOUSE ON MOUNT WILSON

PLATE LXI

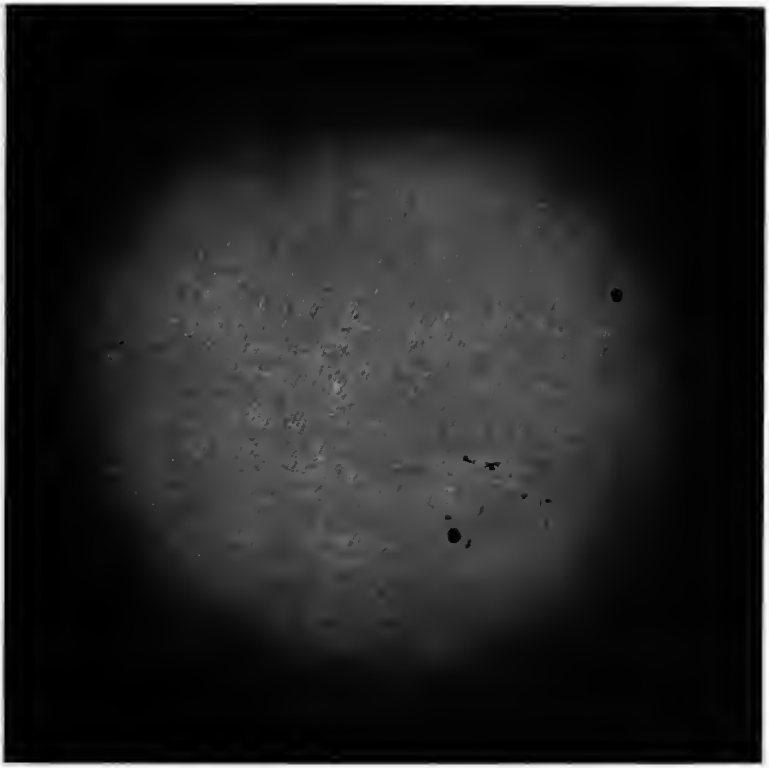
THE 5-FOOT SPECTROHELIOGRAPH, MOUNTED FOR USE WITH THE SNOW TELESCOPE

PLATE LXII



THE 5-FOOT SPECTROHELIOGRAPH WHEN UNDER CONSTRUCTION

PLATE LXIII

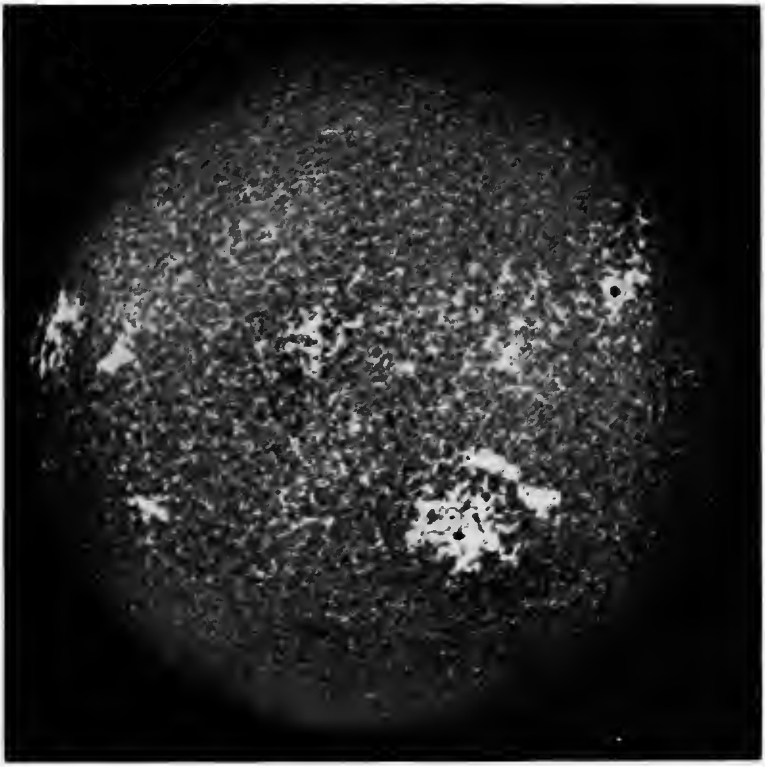


Direct Photograph of the Sun
August 25, 1906, 6h 09m A. M.

PLATE LXIV

THE SUN, PHOTOGRAPHED WITH THE 5-FOOT SPECTROHELIOGRAPH
August 25, 1906, $6^h\ 22^m$ A. M.
Camera slit set on H_1 line of calcium

PLATE LXV



The Sun, Photographed with the 5-foot Spectroheliograph
August 25, 1906, 6h 18m A. M.
Camera slit set on H_2 line of calcium

PLATE LXVI

The Sun, Photographed with the 5-foot Spectroheliograph

August 25, 1906, 6h 36m a. m.

Camera slit set on $H\delta$ line of hydrogen

PLATE LXVII

THE SUN, PHOTOGRAPHED WITH THE 5-FOOT SPECTROHELIOGRAPH
August 25, 1906, 6h 28m A. M.
Camera slit set on the iron line λ 4046

PLATE LXVIII

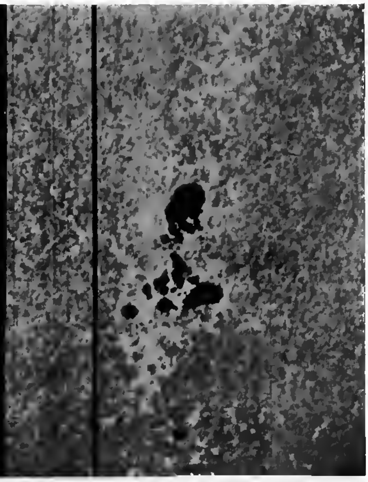
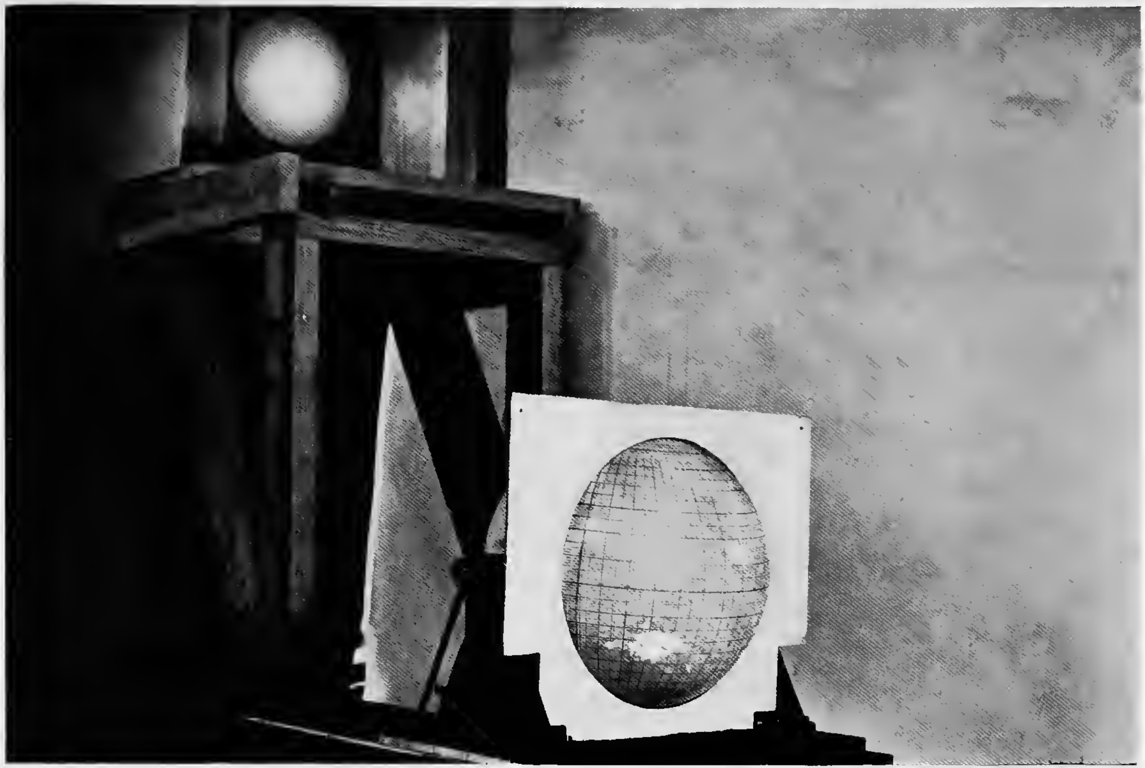


FIG. 1.—7^{h} 46^{m}. Hydrogen Flocculi (H_{δ})

FIG. 2.—7^{h} 54^{m}. Iron Flocculi (λ 4046)

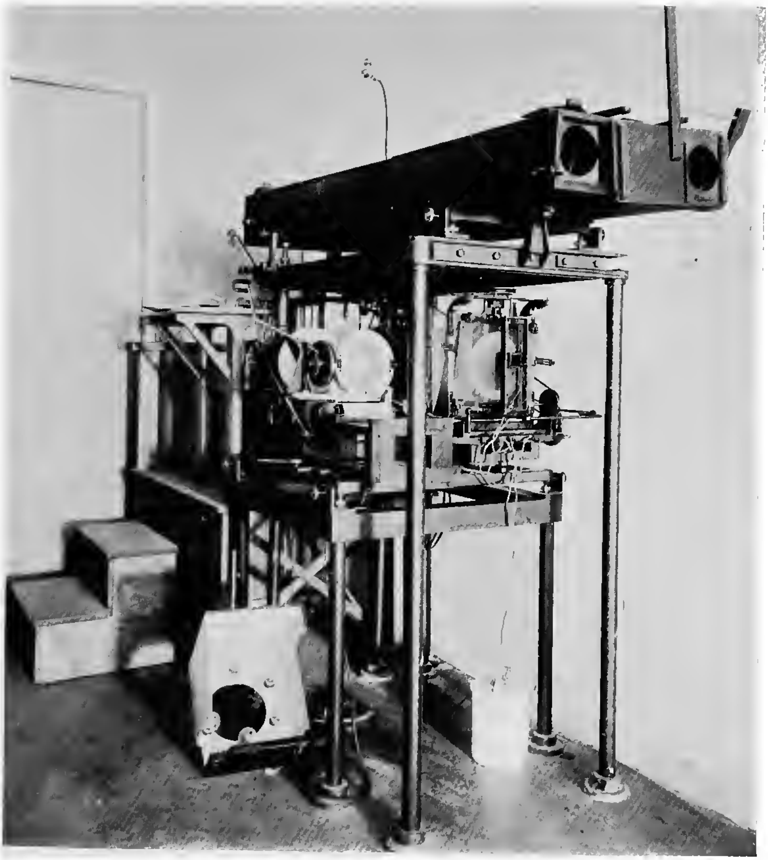
HYDROGEN AND IRON FLOCCULI PHOTOGRAPHED WITH THE 5-FOOT SPECTROHELIOGRAPH, NOVEMBER 13, 1907

PLATE LXIX



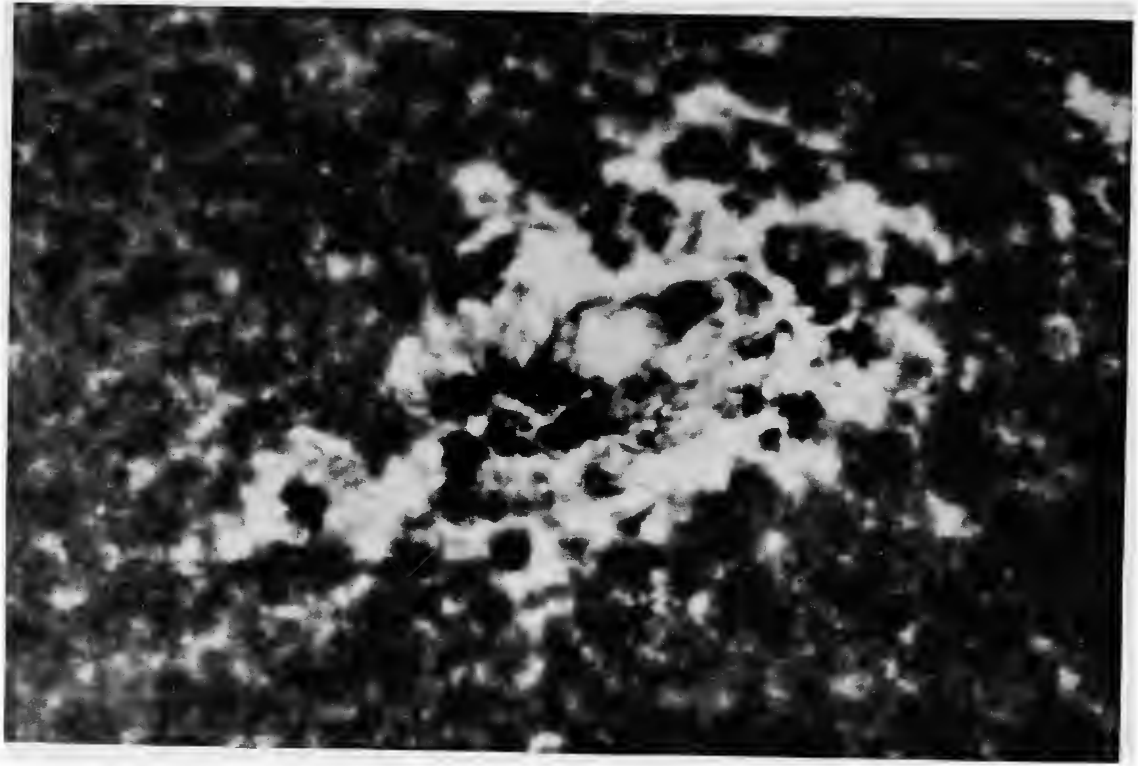
Globe Machine Used at the Yerkes Observatory for Measuring Solar Photographs

PLATE LXX



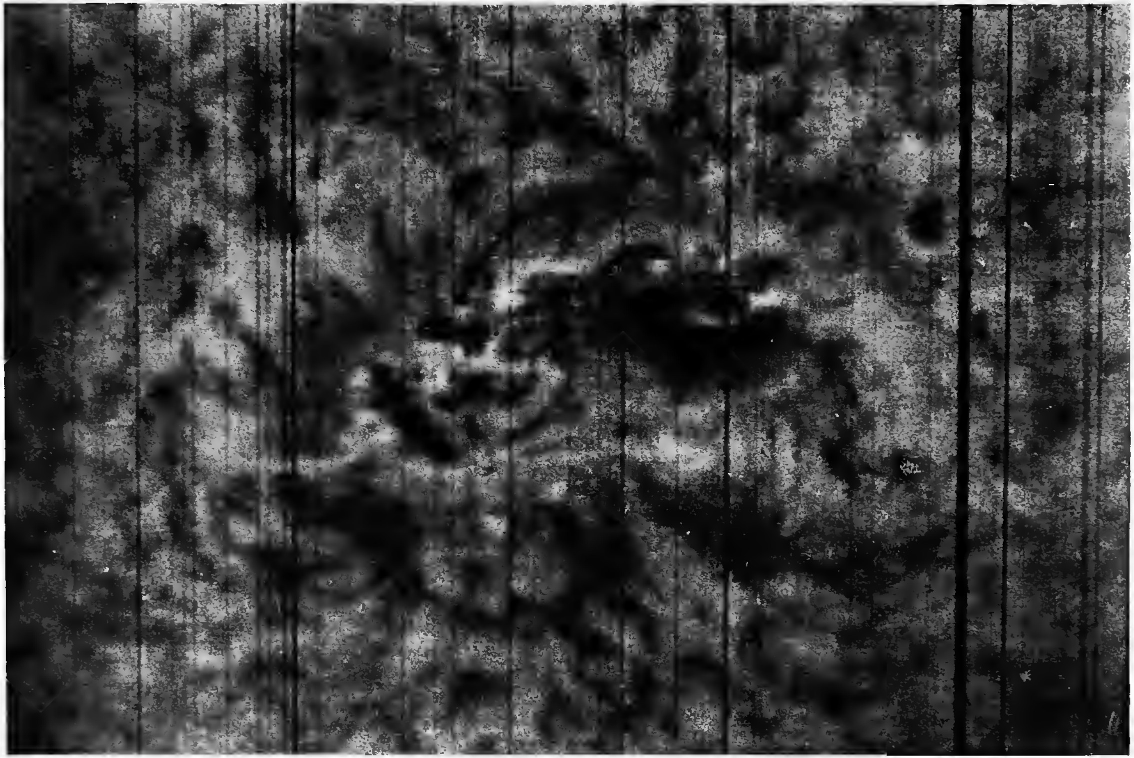
The Heliomicrometer

PLATE LXXI



Bright Calcium Flocculi Surrounding and Overhanging the Great Sun-Spot of October 9, 1903
(Scale: Sun's Diameter = 0.550 Meter)

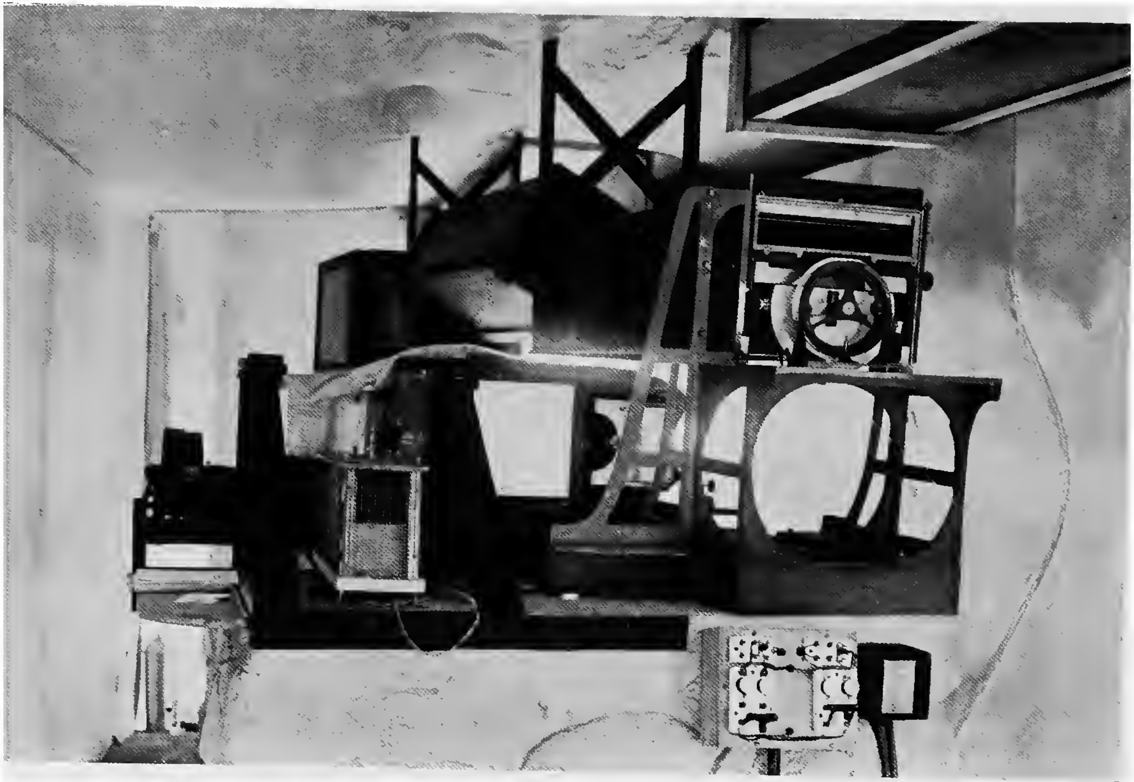
PLATE LXXII



Dark and Bright Hydrogen Flocculi Surrounding the Great Sun-Spot of October 9, 1903

(Scale: Sun's Diameter = 0.550 Meter)

PLATE LXXIII



Littrow Spectrograph, Mounted for Use with Snow Telescope

PLATE LXXIV

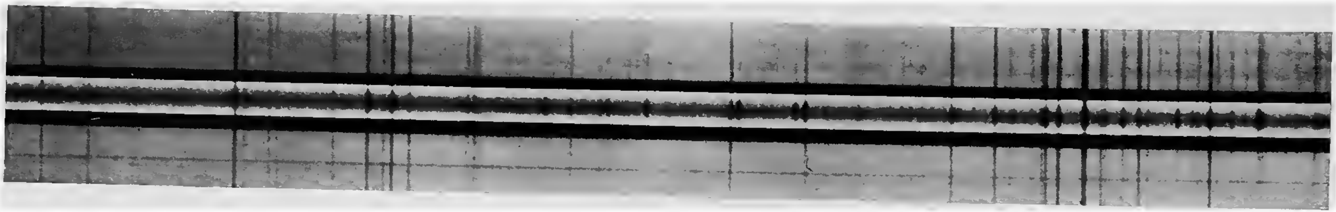


FIG. 1

PHOTOGRAPHIC COMPARISON OF SUN-SPOT SPECTRUM (CENTER) WITH THE NORMAL SOLAR SPECTRUM

(Region: λ 5695–λ 5775)

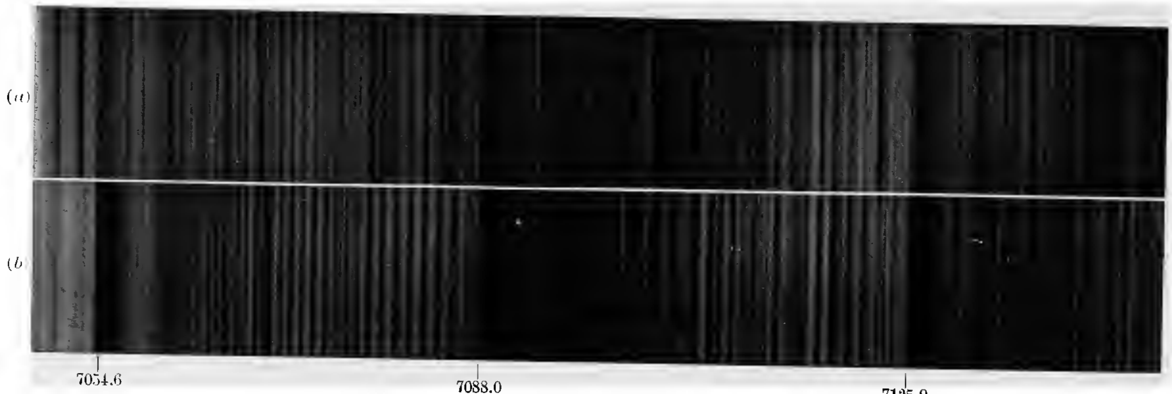


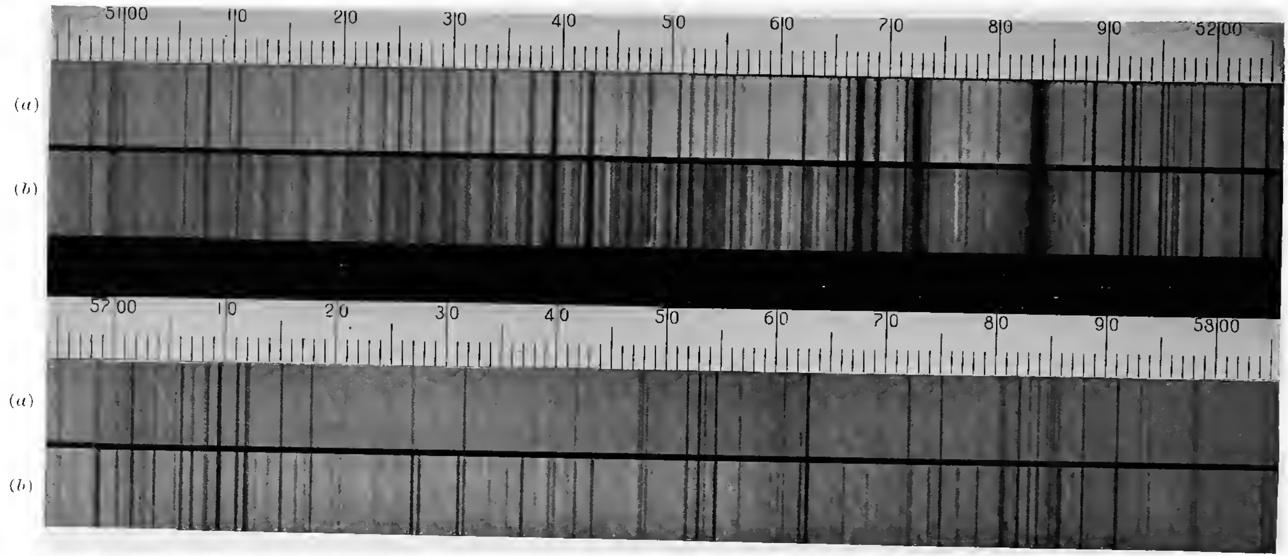
FIG. 2

TITANIUM OXIDE FLUTINGS IN SPECTRA OF (a) SUN-SPOT AND (b) FLAME OF ELECTRIC ARC

PLATE LXXV

THE SPECTROSCOPIC LABORATORY ON MOUNT WILSON

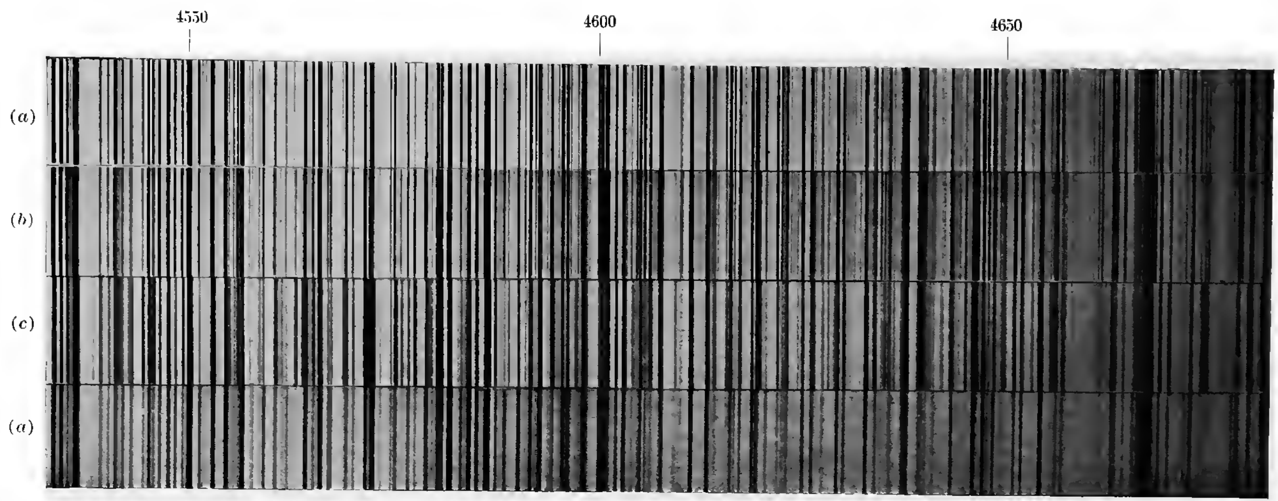
PLATE LXXVI



Two Sections of the Mount Wilson Preliminary Photographic Map of the Sun-Spot Spectrum

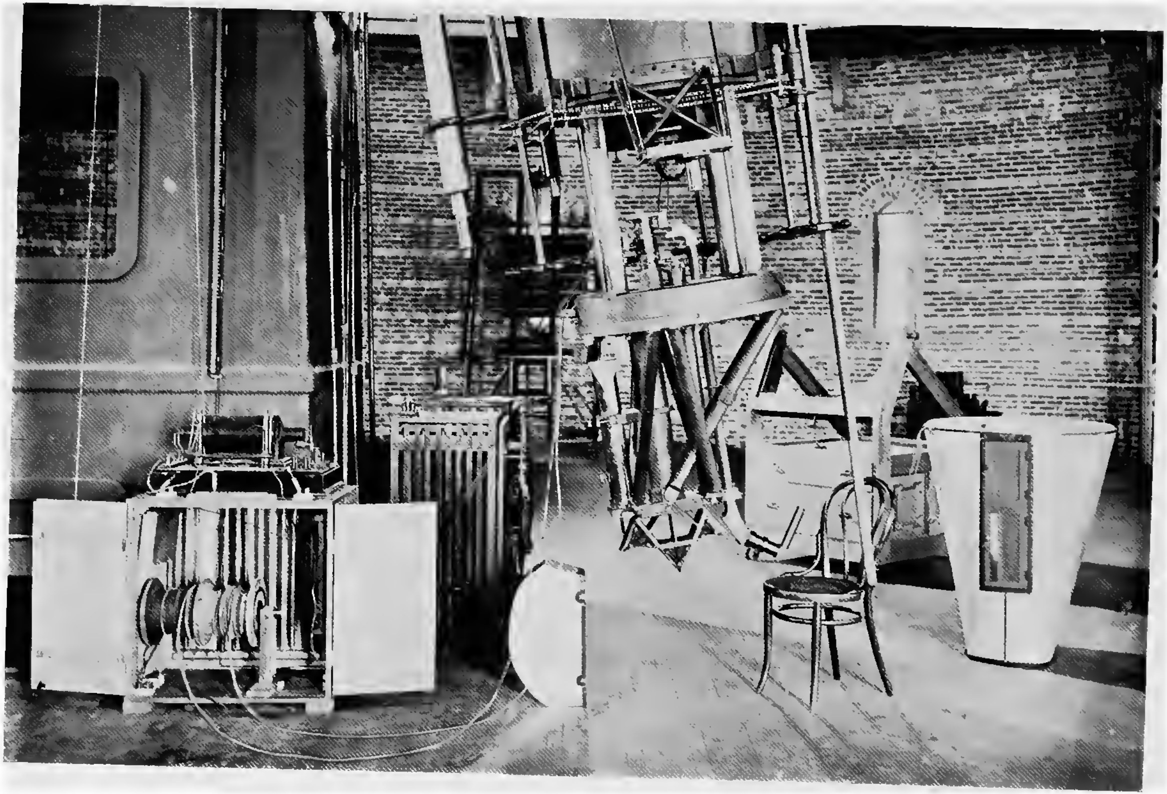
(a) Normal solar spectrum, (b) Sun-spot spectrum

PLATE LXXVII



Photographs of the Spectra of (a, a) the Sun, (b) *Arcturus*, (c) Sun-Spot

PLATE LXXVIII



Bruce Spectrograph Attached to 40-inch Yerkes Refractor

PLATE LXXIX

SPECTRA OF *RR Scorpii* AND OTHER STARS
Photographed with objective prism at the Harvard Observatory

PLATE LXXX

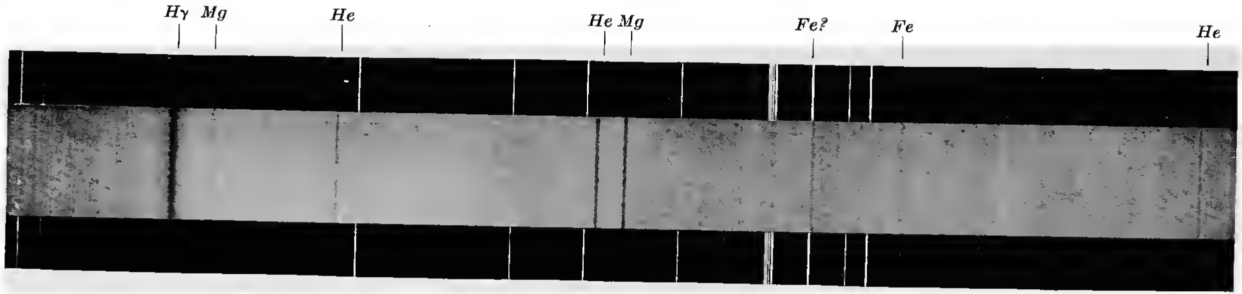


FIG. 1.—β *Orionis*

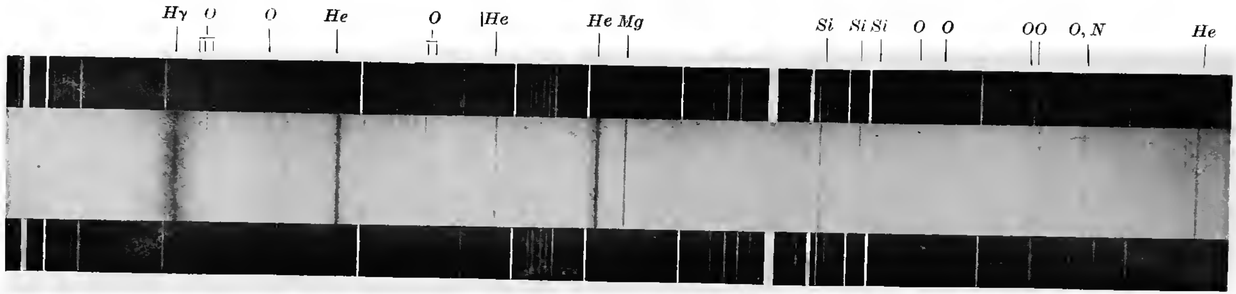


FIG. 2.—β *Canis Majoris*

STELLAR SPECTRA OF THE *Orion* TYPE PHOTOGRAPHED WITH THE BRUCE SPECTROGRAPH

(Frost and Adams)

With comparison spark spectrum of titanium

PLATE LXXXI

FIG. 1.—*Sirius*

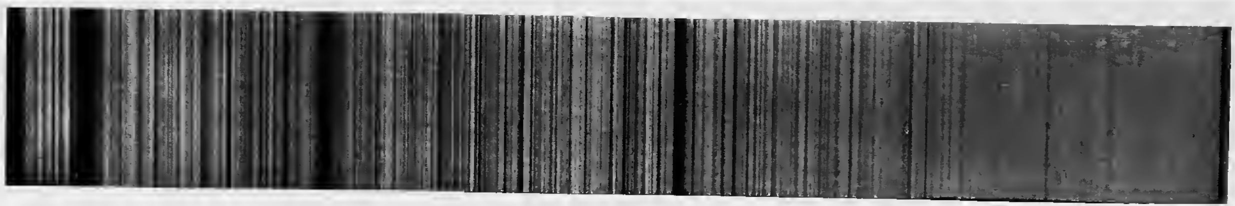


FIG. 2.— *Procyon*

STELLAR SPECTRA PHOTOGRAPHED WITH THE BRUCE SPECTROGRAPH
(Frost)

PLATE LXXXII

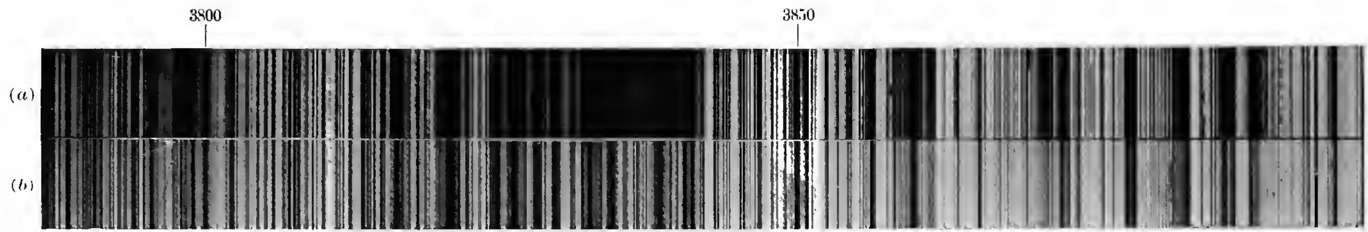


FIG. 1

FIG. 2

SPECTRUM OF SUN (a) AT CENTER AND (b) NEAR LIMB

PLATE LXXXIII

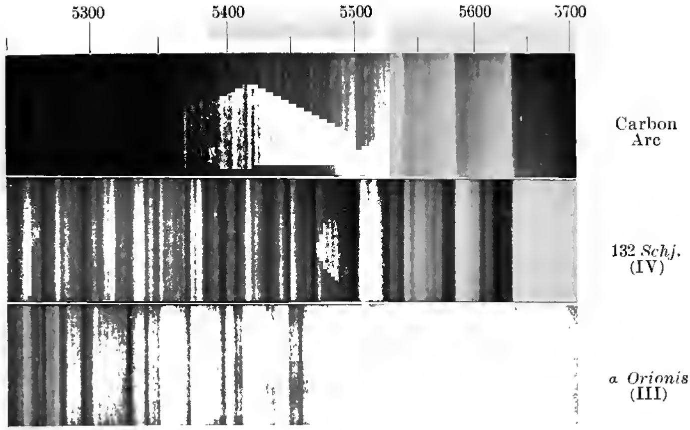


FIG. 1

REGION OF YELLOW CARBON FLUTING IN ELECTRIC ARC, FOURTH TYPE STAR (132 *Schjellerup*), AND THIRD TYPE STAR (*a Orionis*)

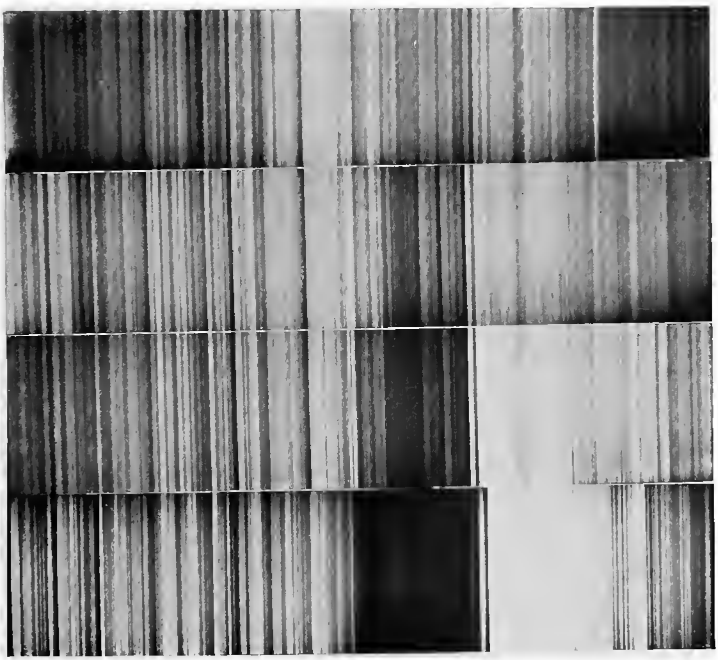
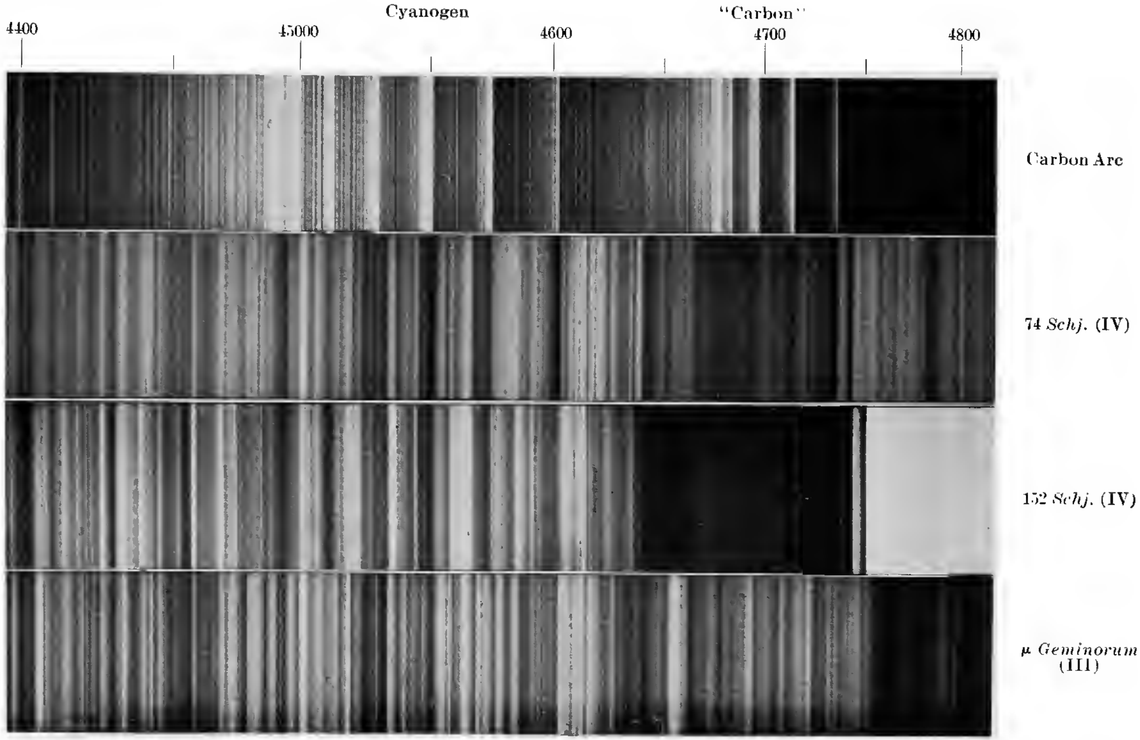


FIG. 2

SPECTRA OF FOUR FOURTH TYPE STARS

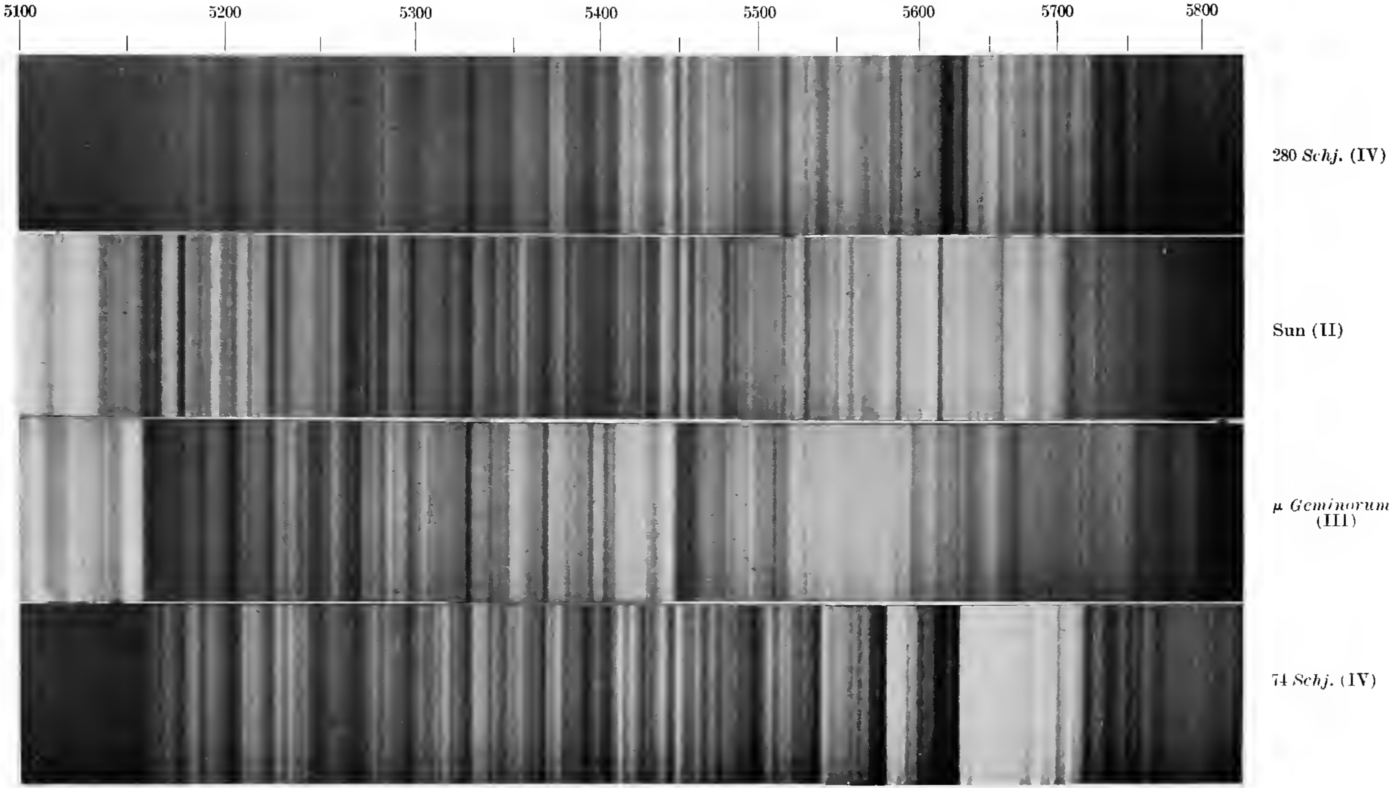
Photographed with the 40-inch Yerkes refractor, showing how the dark carbon band becomes stronger as the star cools

PLATE LXXXIV



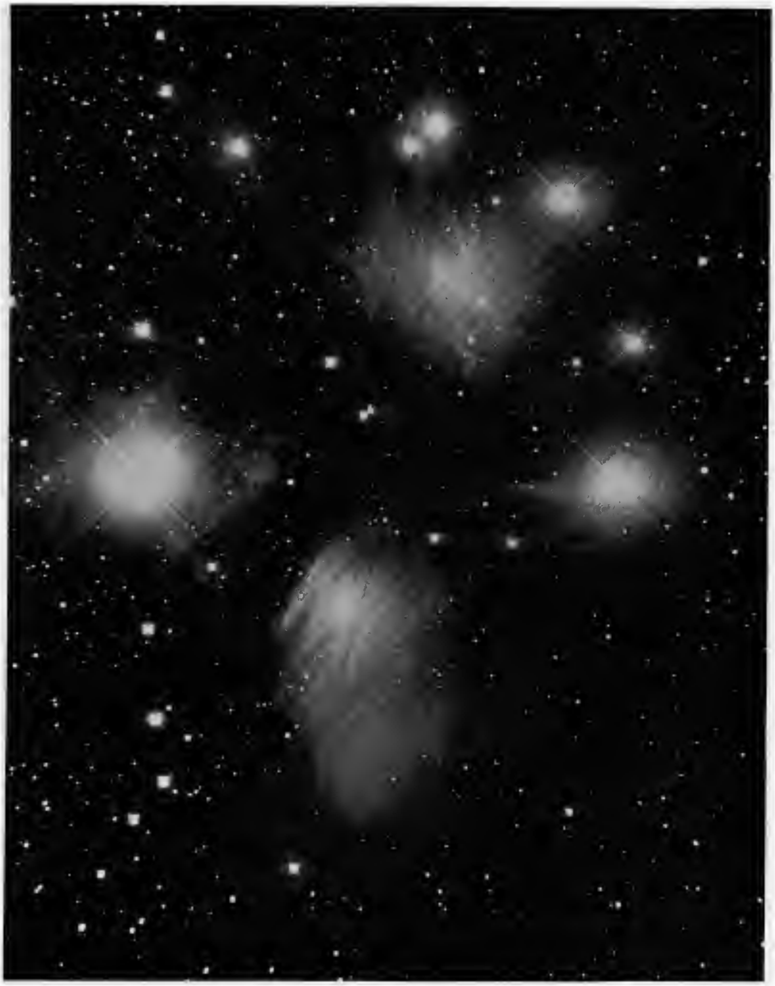
Blue Cyanogen and Carbon Flutings in Electric Arc Compared with Spectra of Third and Fourth Type Stars

PLATE LXXXV



Comparison of Stellar Spectra of Second, Third and Fourth Types

PLATE LXXXVI



THE PLEIADES

Photographed with the 24-inch reflector of the Yerkes Observatory (Ritchey)

PLATE LXXXVII

NEBULA IN *Cygnus*, *N. G. C.* 6992

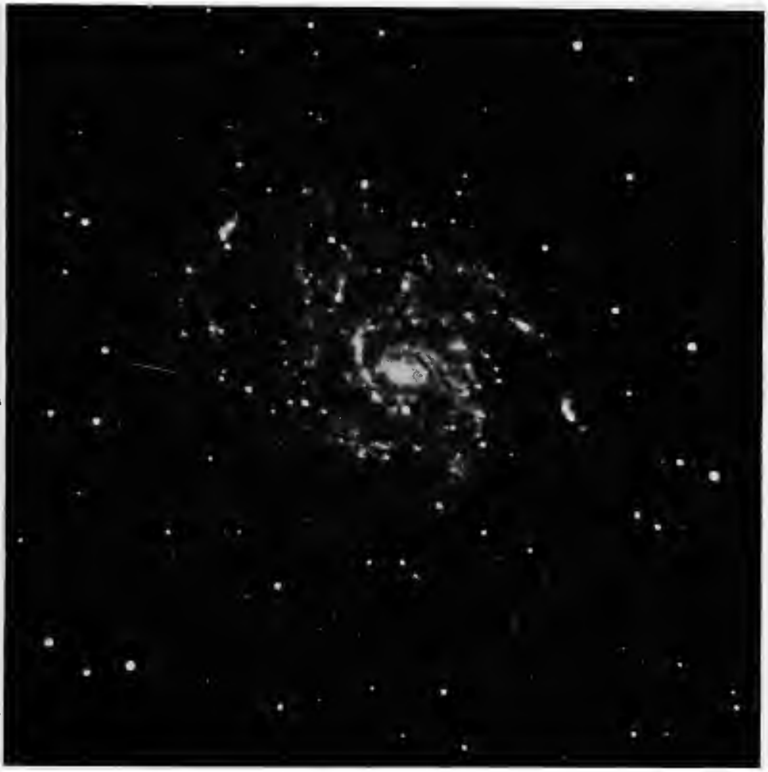
Photographed with the 24-inch reflector (Ritchey)

PLATE LXXXVIII

SPIRAL NEBULA *Messier* 51 *Canum Venaticorum*

Photographed with the 24-inch reflector (Ritchey)

PLATE LXXXIX



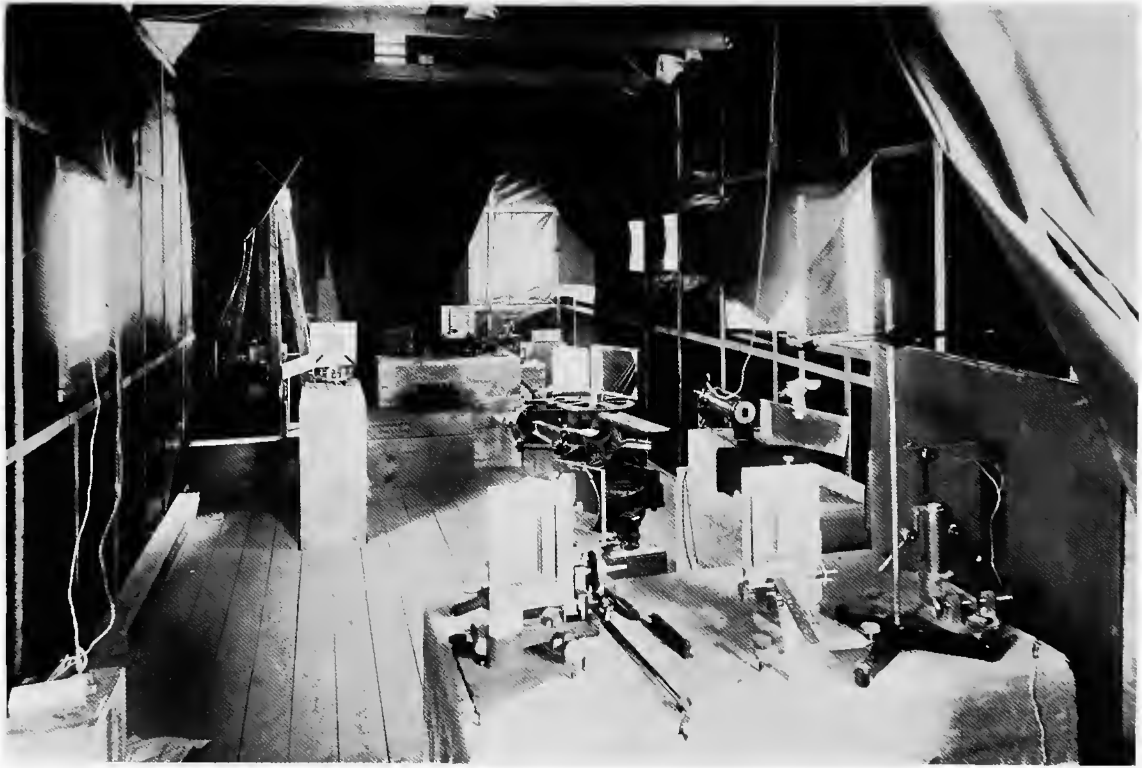
SPIRAL NEBULA *Messier* 101

Photographed with the 24-inch reflector (Ritchey)

PLATE XC

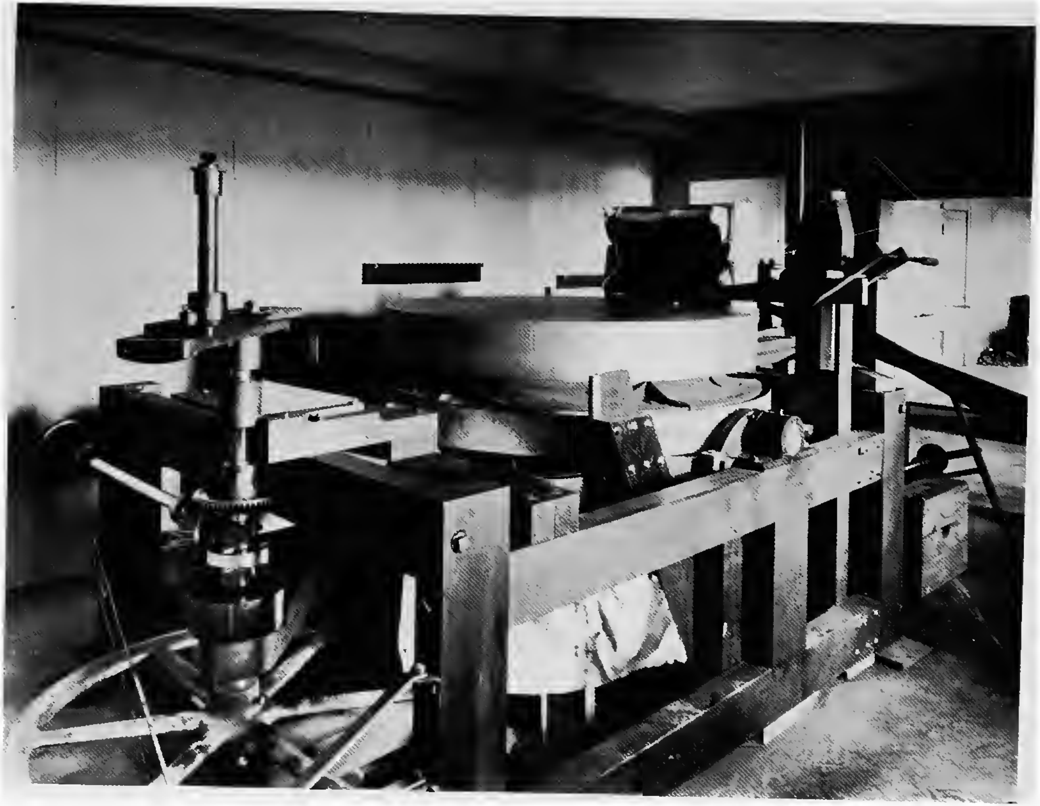
Spiral Nebula *Messier* 33 *Trianguli*
Photographed with the 24-inch reflector (Ritchey)

PLATE XCI



Bolometric Apparatus Used by Smithsonian Expedition on Mount Wilson

PLATE XCII



Grinding the Edge of the 60-inch Mirror

PLATE XCIII

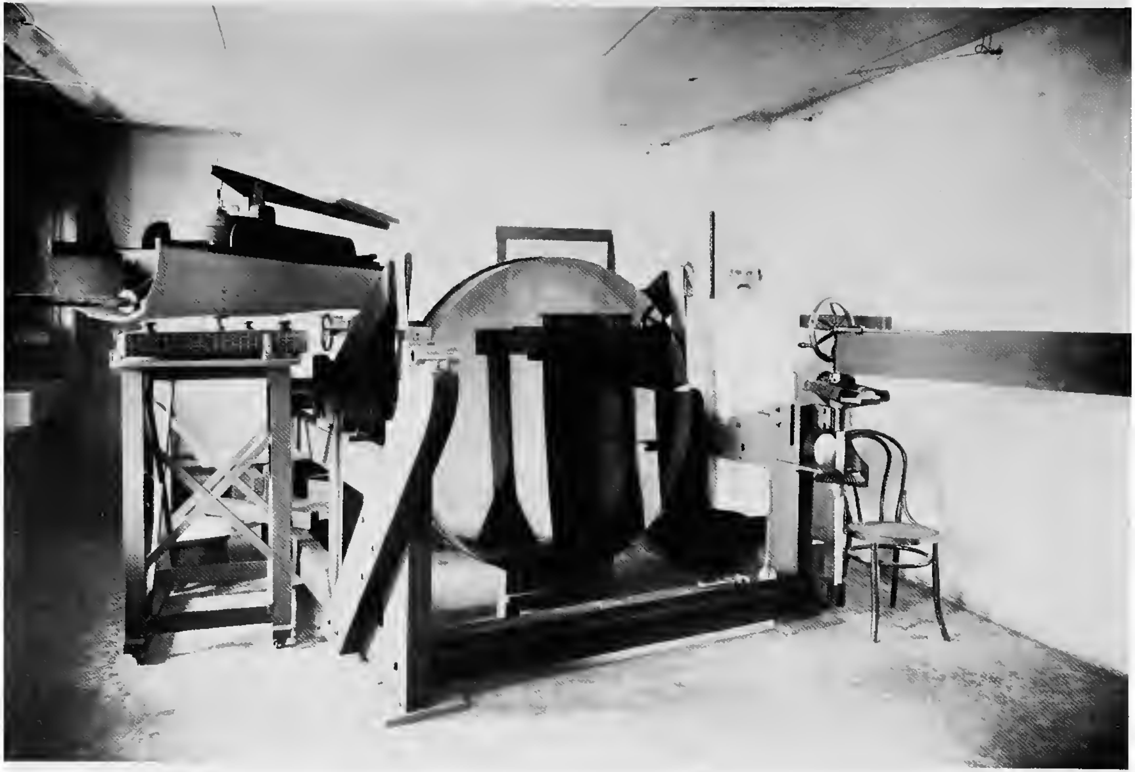
60-INCH MIRROR AND GRINDING MACHINE

Showing full-size iron grinding-tool suspended on lever

PLATE XCIV

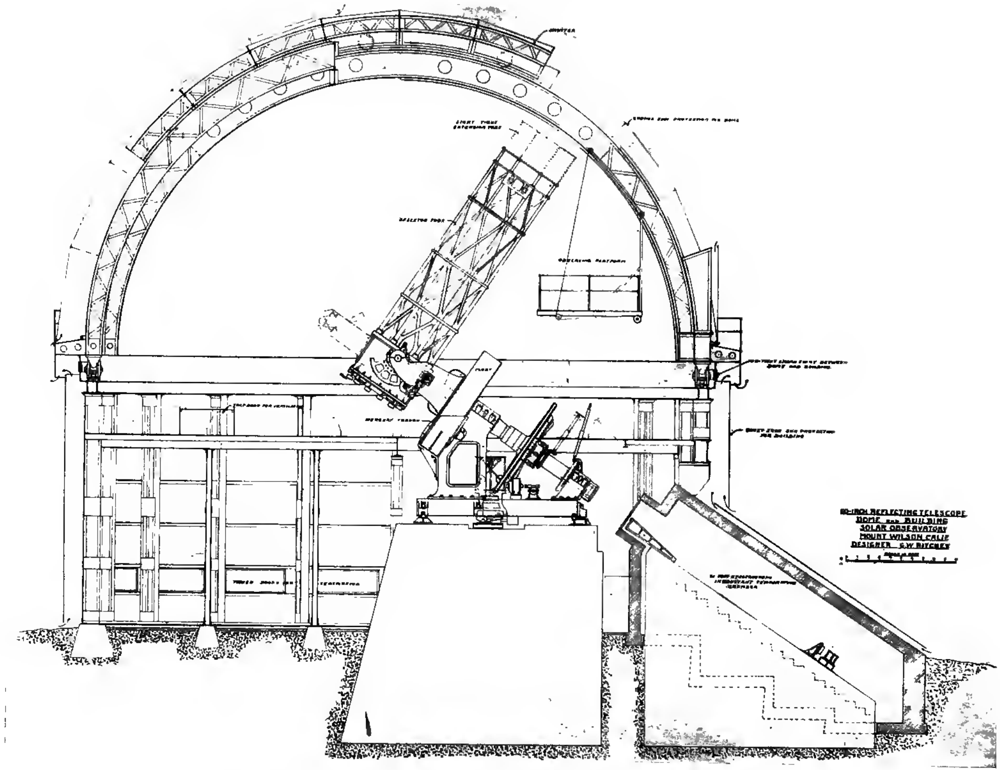
60-inch Disk after Both Surfaces had been Fine-Ground and Polished

PLATE XCV



60-inch Mirror Turned Down for Testing

PLATE XCVI



DOME AND MOUNTING FOR 60-INCH REFLECTING TELESCOPE

PLATE XCVII

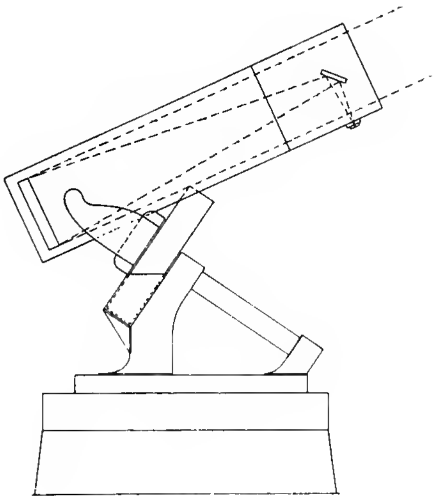


FIG. 1

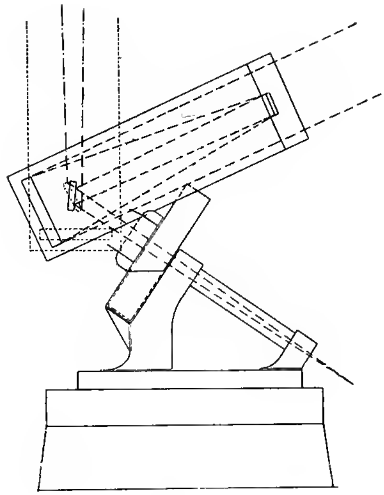


FIG. 2

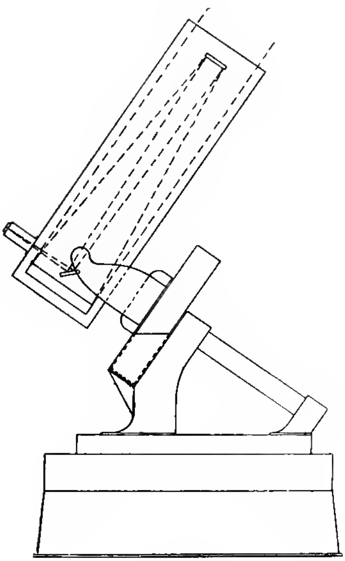


FIG. 3

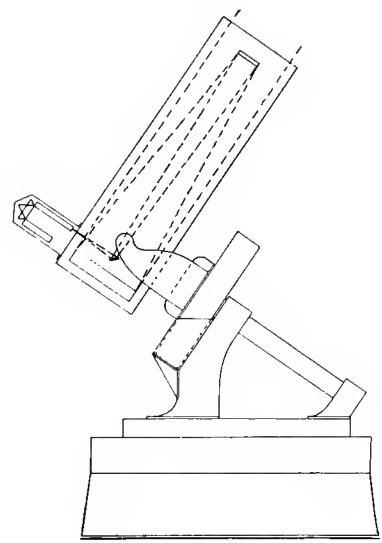
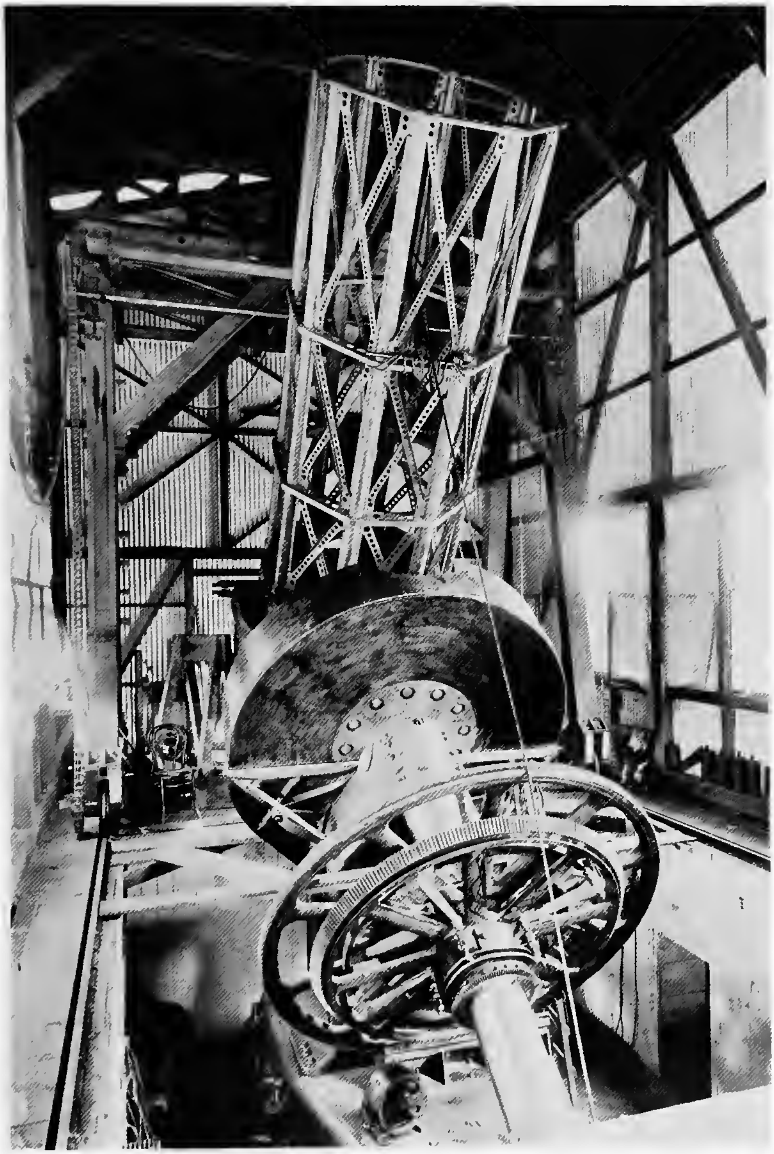


FIG. 4

VARIOUS MIRROR COMBINATIONS IN 60-INCH REFLECTING TELESCOPE

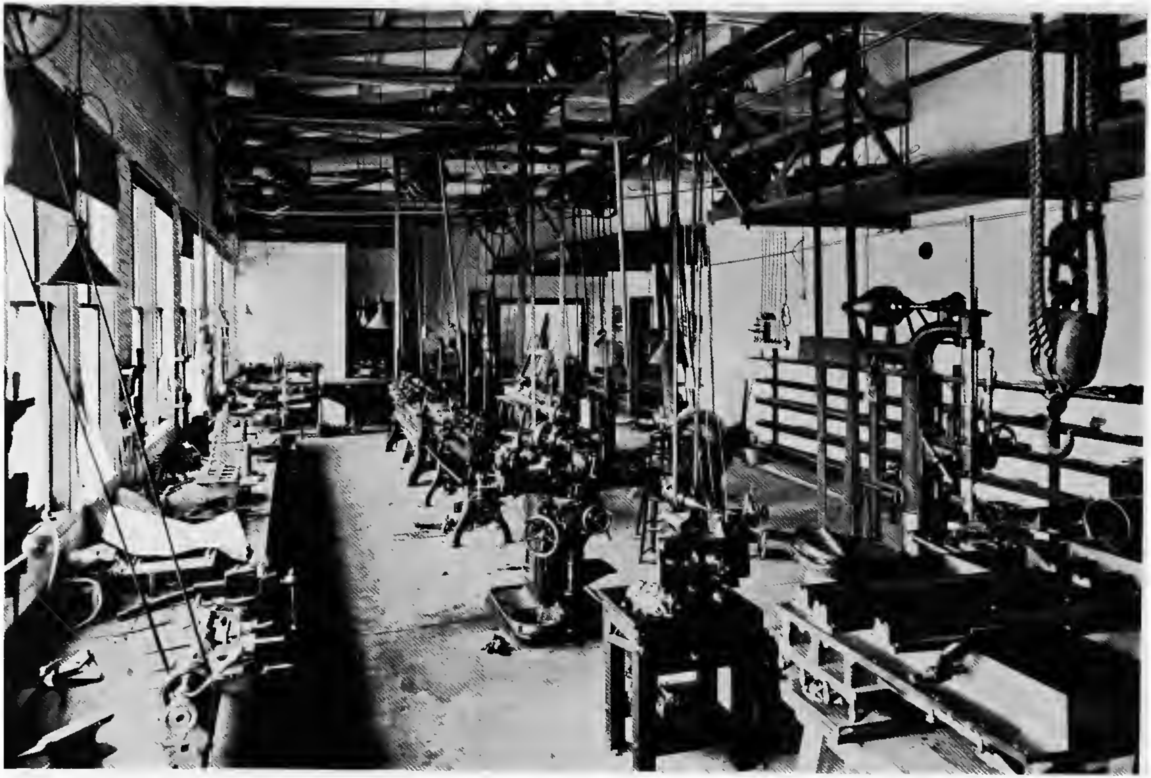
PLATE XCVIII



Mounting of 60-inch Reflecting Telescope

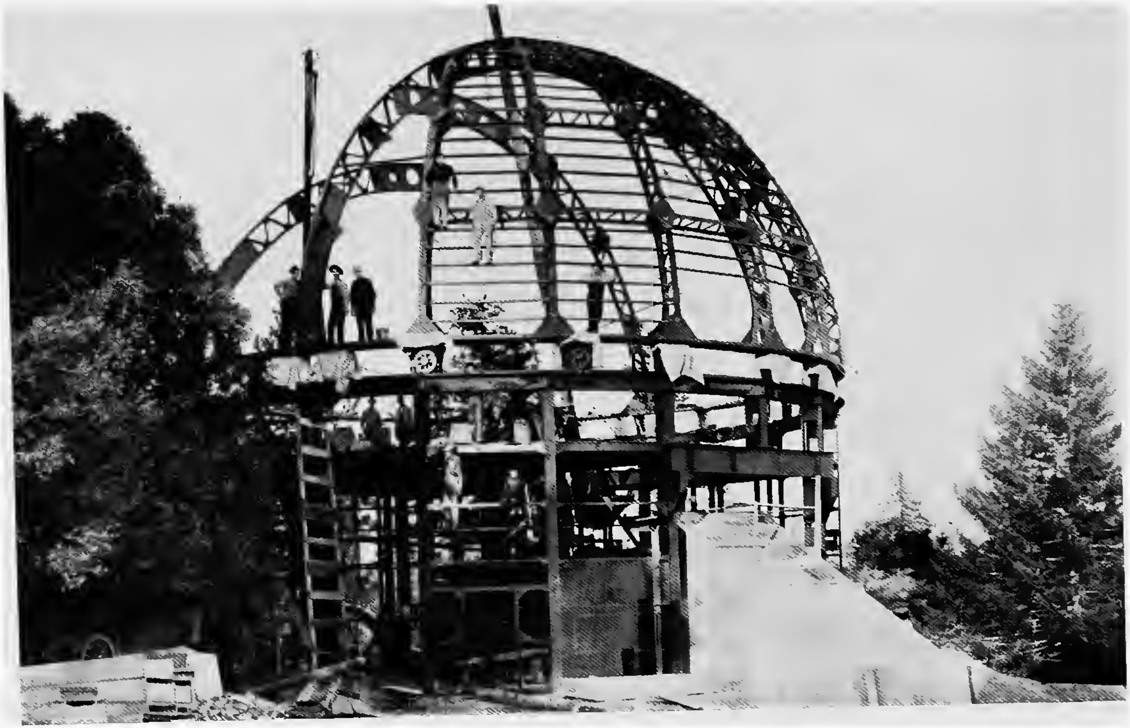
Under construction in Pasadena instrument shop of the Solar Observatory

PLATE XCIX



Pasadena Instrument Shop of the Solar Observatory

PLATE C



Steel Building and Dome for 60-inch Reflecting Telescope

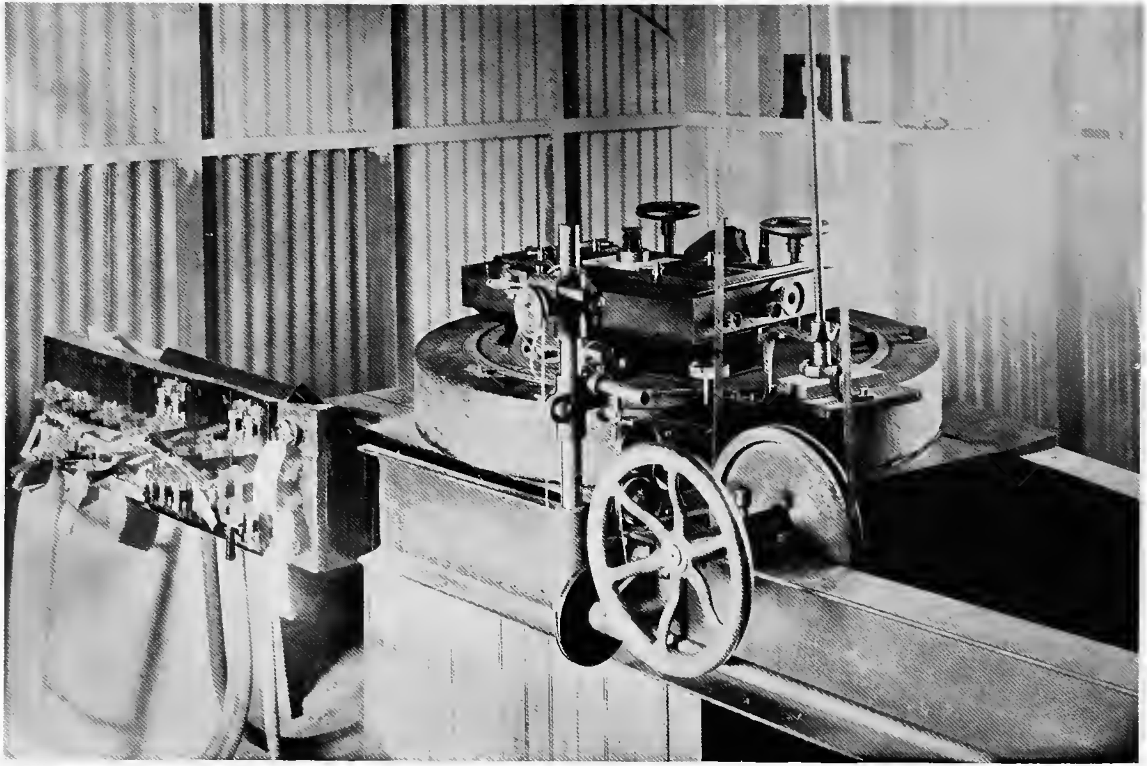
Under construction on Mount Wilson (October, 1907)

PLATE CI

Tower Telescope on Mount Wilson

The Snow telescope building appears beyond the tower

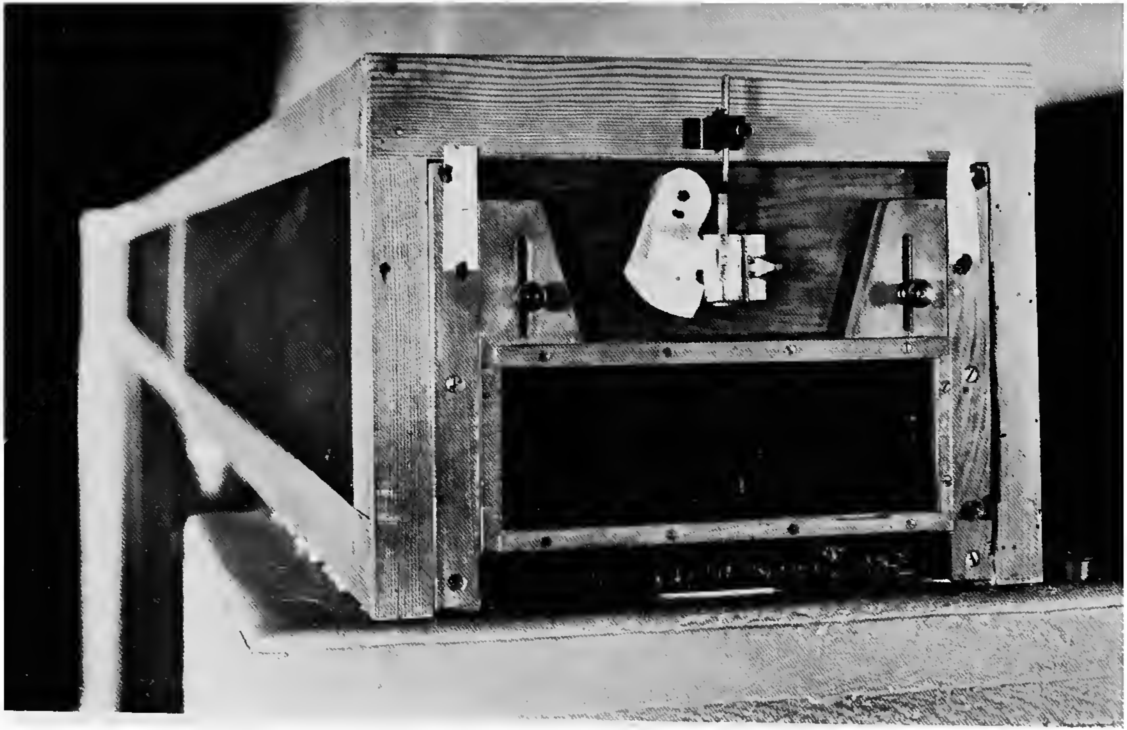
PLATE CII



30-foot Spectrograph of the Tower Telescope

PLATE CIII

Wooden Lens and Grating Support of Littrow Spectrograph



Slit and Plate-Holder of Littrow Spectrograph